EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF TIP CLEARANCE AND END LOSSES ON AXIAL COMPRESSOR PERFORMANCE

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THESIS

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Effects of Tip Clearance and End
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ABSTRACT

The objective of this study was to determine by experimental means the rotor efficiencies at different radii between hub and tip of a single stage axial compressor at its design point, to show the influence of tip clearance and end losses.

Procedure for calibration and application of pressure probes to survey the flow in the compressor were established, and programs were written to analyze the measured data.

Recommendations are made for improvements of the data reduction methods, which should precede experiments involving controlled changes in the blade tip clearances.

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I. INTRODUCTION

The performance of axial flow compressors is greatly affected by the blade end and tip clearance losses. No accurate methods exist to predict these losses for arbitrary conditions. The main objective of this study was to determine by experimental means the rotor blade efficiencies of a single stage compressor at its design point at different radii between hub and tip. This efficiency distribution will indicate by how much the so-called profile losses are increased by blade end effects.

At a future date the tests will be repeated with different tip clearances to obtain a better understanding of the physical aspects of the rotor flows near the blade tips. This study has been undertaken to establish the necessary measuring procedure and to set up a data reduction method that can be used for these tip clearance tests.

The present tests were carried out with a single stage that had solid body rotation bladings designed for forced-vortex flow. It was installed in a research compressor of the Turbo-Propulsion Laboratory of the Department of Aeronautics at the Naval Postgraduate School. The compressor has a nominal tip diameter of 36 inches and a hub-to-tip ratio of 0.6. It is driven by a 150 horsepower electric motor at a speed of about 2300 revolutions per minute, giving a tip speed of 360 feet per second.

The compressor is throttled ahead of the inlet and discharges into the atmosphere through a conical diffusor. The throttling device is installed between the inlet bellmouth and the compressor inlet. It consists of a chamber in which a number of different wire mesh screens or perforated plates can be installed to create the desired pressure rise in the compressor. To operate the compressor along its characteristics, it is

necessary to change the arrangement of wire mesh and perforated plates. Such changes will be carried out to establish the design point of the stage, which is considered to be the operating point where the highest efficiency is reached.

The local rotor efficiencies between hub and tip can be determined by taking flow surveys ahead of and after the rotor at a number of radii. Because of the three-dimensional nature of flows in turbomachines, it is necessary to determine the velocities and flow angles in axial, peripheral and radial directions at each point of a survey. Such measurements are made using 5-hole pressure probes, Type DA 120, of the United Sensor Corporation. However, these probes must be calibrated in a flow with known velocities and direction at roughly the same Mach numbers as exist in the actual compressor.

II. EXPERIMENTAL CALIBRATION OF SURVEY PROBES

A. INTRODUCTION

The testing apparatus used to calibrate the 5-hole United Sensor type DA 120 survey probes is shown in Fig. 1. A Kiel probe was arranged as shown to serve as a reference measurement. Fig. 2 shows a typical Kiel probe. Particular pitch angles could be set by use of the apparatus shown in Fig. 6. Pitch and yaw angles were defined according to Fig. 5. Vertical surveys were restricted to zero pitch angle.

The mass flow rate from the Allis-Chalmers compressor to the test section was controlled by a gate valve.

B. FLOW FIELD DETERMINATION

The most accurate probe available is the so-called Prandtl pitot-static probe of Fig. 3 which measures true static and total pressure. It served as the reference for calibration of the 5-hole probes. Velocity profiles were obtained in the horizontal and vertical direction of the calibrating duct with this probe.

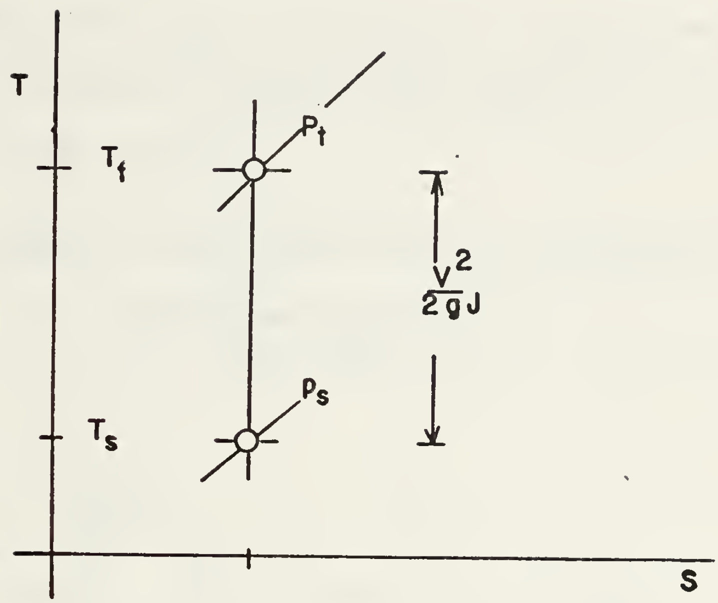
For an isentropic process ahead of the probe, the velocity V is, from the following figure,

$$\frac{V^2}{2gJ} = c_p \,(T_t - T_s)$$

For a constant value of the specific heat ratio γ ,

$$\frac{T_s}{T_t} = \left(\frac{p_s}{p_t}\right)^{\frac{\gamma-1}{\gamma}}$$

Thermodynamic Process in
Prandtl Probe



Introducing the speed of sound a_t , at the total temperature T_t , the following non-dimensional velocity was obtained:

$$\frac{V}{a_t} = \left(\frac{2}{\gamma-1}\left\{1 - \left(\frac{p_s}{P_t}\right)^{\frac{\gamma-1}{\gamma}}\right\}\right)^{\frac{1}{2}} \tag{1}$$

If $\Delta P = P_t - p_s$ is small compared with the absolute total pressure P_t , Equation (1) can be expressed by the approximation:

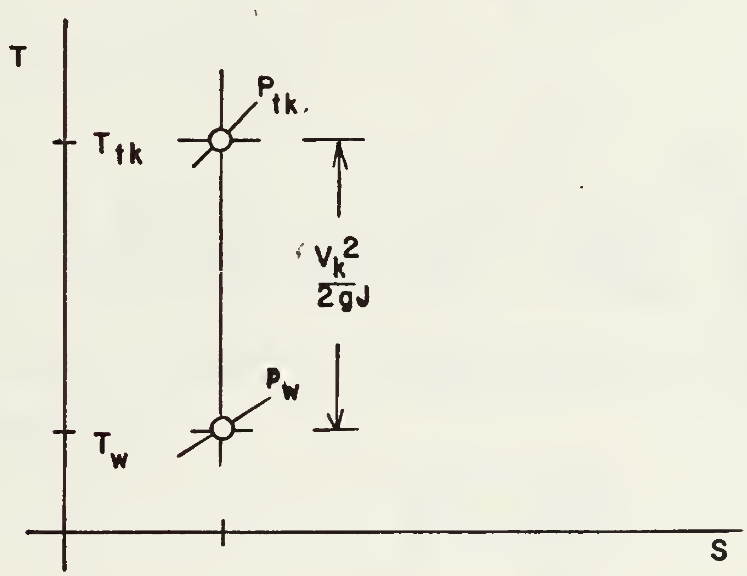
$$\frac{V}{a_t} = \left(\frac{2}{\gamma} \cdot \frac{\Delta P}{P_t}\right)^{\frac{1}{2}} \tag{2}$$

Surveys were performed in the horizontal and vertical directions in the calibrating pipe at various mass flow rates to cover the range of velocities that were experienced in the compressor. The readings of the

Kiel probe, P_{tk} and T_{tk}, and of the wall static tap in its vicinity, p_w, were used as reference values for different mass flow rates and inlet conditions. Figs. 9 to 11 indicate a region of uniform velocity in the center region of the pipe. A position 4.5 inches from the right-hand wall along the horizontal centerline was chosen as the location for subsequent 5-hole probe surveys.

C. CALIBRATION FACTORS OF 5-HOLE PROBES TYPE DA 120 #535 AND #538

Thermodynamic Process in
Kiel Probe



As seen in the above figure,

$$\frac{V_k^2}{2gJ} = c_p \, (T_{tk} - T_w)$$

Similar to Equation (1), with a_{tk} being the speed of sound for the total temperature obtained from the thermocouple of the Kiel probe,

$$\frac{V_k}{a_{tk}} = \left(\frac{2}{\gamma-1}\left\{1 - \left(\frac{p_w}{P_{tk}}\right)^{\frac{\gamma-1}{\gamma}}\right\}\right)^{\frac{1}{2}} \tag{3}$$

The mass flow rate at the location of the Kiel probe is obtained from

$$\dot{m} = A\ K_{BK}\ \xi_k \frac{V_k}{v_k} \tag{4}$$

where K_{BK} is a blockage factor, ξ_k a correction factor for the velocity profile if p_w is not the true static pressure and v_k is the specific volume. With $P_{tk}\ v_{tk}^{\gamma} = p_w\ v_k^{\gamma}$,

$$v_k = \frac{R_G\ T_{tk}}{P_{tk}} \frac{1}{(p_w/P_{tk})^{1/\gamma}} \tag{5}$$

Equations (3) and (5) give:

$$\frac{\dot{m}\ \sqrt{R_G/g\ T_{tk}}}{A\ K_{BK}\ \xi_k\ P_{tk}} = \left(\frac{2\gamma}{\gamma-1}\left\{\left(\frac{p_w}{P_{tk}}\right)^{2/\gamma} - \left(\frac{p_w}{P_{tk}}\right)^{\frac{\gamma+1}{\gamma}}\right\}\right)^{\frac{1}{2}} = \Phi \tag{6}$$

Since $p_w = P_{tk} - \Delta$, and Δ was small compared to P_{tk} , Equation (6) was approximated by,

$$\Phi = \sqrt{2\left(1 - \frac{p_w}{P_{tk}}\right)} \tag{7}$$

A similar expression was established for the mass flow rate at the location of the Prandtl probe by assuming that the total temperature was constant in the pipe, or

$$\frac{\dot{m}\ \sqrt{R_G/g\ T_{tk}}}{A\ K_{BP}\ \xi_P\ P_t} = \sqrt{2\left(1 - \frac{p_s}{P_t}\right)} \tag{8}$$

Since $\dot{m}$ and A are equal in Equations (6) and (8) there is

$$\Psi \equiv \left(\frac{K_{BK}\ \xi_K}{K_{BP}\ \xi_P}\right)^2 = \frac{P_t}{P_{tk}}\left(\frac{P_t - p_s}{P_{tk} - p_w}\right) \tag{9}$$

Therefore, with the measured quantities P_t and p_s of the Prandtl probe, the total pressure P_{tk} of the Kiel probe and the wall pressure p_w near the Kiel probe, it is possible to establish the coefficient Ψ, provided that the above mentioned data are taken at the same flow rate $\dot{m}$. The value of Ψ will depend primarily on the Mach number of the flow because Reynolds number effects are small in turbulent flows. For isentropic processes

$$\frac{P_t}{p_s} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

where P_t, p_s are the total and static pressures, respectively, and M is the actual Mach number at the pressure p_s. Hence, for the same specific heat ratio γ, the Mach number M is only a function of the pressure ratio P_t/p_s and is independent of the temperature of the fluid. Therefore, it is possible also to consider the ratio

$$M_k = \frac{P_{tk} - p_w}{P_{tk}} = 1 - \frac{p_w}{P_{tk}} \tag{10}$$

as a measure for the actual Mach number M.

Measurements with the Prandtl and Kiel probes at different flow rates, resulting in different values of M_k, gave the relationship between Ψ and M_k that is presented in Fig. 10.

Rearranging Equation (9) gives the velocity head as

$$P_t - p_s = \Psi \frac{P_{tk}}{P_t}(P_{tk} - p_w) \tag{11}$$

Replacing the Prandtl probe with the 5-hole probe and defining

$$K_Q \equiv \frac{P_t - p_s}{P_1 - P_2} \tag{12}$$

it follows,

$$K_Q = \Psi \frac{P_{tk}}{P_1} \frac{\left(P_{tk} - p_w\right)}{P_1 - P_2} \tag{13}$$

where $P_1 = P_t$ is the total pressure and P_2 is the approximate static pressure measured by the 5-hole probe. The location of the pressure ports for the 5-hole probes is seen in Figs. 4 and 5.

Similar to Equation (10),

$$M_r = \frac{P_1 - P_2}{P_1} \tag{14}$$

The relationship between K_Q and M_r is shown in Figs. 11, 12 and 15 for the two probes calibrated. These graphs make it possible to determine the true velocity head of the 5-hole probe for a measured M_r.

Different pitch angles were set with the device of Fig. 6. The pressure difference between P_4 and P_5 is a measure of the pitch angle θ. With

$$K_\theta = \frac{P_4 - P_5}{P_1 - P_2} , \tag{15}$$

the relationship between this pressure difference and pitch angle is shown in Figs. 14 and 17. The relationship between K_Q and θ is shown in Figs. 13 and 16. By rotating the 5-hole probes about their axes, P_2 and P_3 were balanced and the yaw angle was read directly from a protractor mounted on the supported frame of the probe.

III. ONR THREE STAGE AXIAL FLOW COMPRESSOR

Figs. 18 and 19 show the compressor installation at the Turbo-Propulsion Laboratory. This test rig will be described in detail in a report of the Department of Aeronautics, which is being prepared.

The compressor was designed for a variety of research experiments. Six rectangular ports are arranged in the upper casing to accommodate the survey probe carriage shown in Fig. 20. The location of these ports makes it possible to survey circumferentially in a 15° arc at positions ahead of and after the rotors and stators.

The rotor and stator blades are removable and during this study only the first rotor and third stator were installed. The relative position of the rotor and stator for this "expanded" single stage configuration is seen in Fig. 21.

The stator and rotor blade profiles of the solid body rotation stage are shown in Fig. 22. The blade chords varied from 2.00 to 3.40 inches. The solidity of the rotor varied from 1.150 to 0.903 from hub to tip and that of the stator from 1.039 to 0.850.

Inlet guide vanes (IGV) are located ahead of the rotor and two rows of exit guide vanes (EGV) are located after the compressor stage.

There are thirty rotor blades per row and thirty-two IGV's, stator blades, and EGV's per row.

A more detailed description of the blading is given in Ref. 2.

As shown in Fig. 23, Kiel probes were located in the survey holes along the length of the compressor, which measure the total pressure at fixed radial positions.

The inlet bellmouth was surrounded by a screen enclosure to reduce disturbances by wind gusts.

IV. INSTRUMENTATION

Wet and dry bulb mercury glass thermometers were located on the inlet screen to determine the relative humidity of the air entering the bellmouth. A program for determining the gas constant R_G for different humidities is given in Appendix B.

The pressure drop across the inlet nozzle was measured with a Meriam Micromanometer, seen in Fig. 24, which had a reading accuracy of 0.001 inch of water.

Kiel probes were located in the survey holes and static pressure taps were located in the same meridional plane. These pressures were measured on the large water manometer board of Fig. 25.

A United Sensor 5-hole probe was located in the survey carriage, seen in Fig. 20, and the various pressures were read from the U-tube manometer board of Fig. 25.

Forward and aft bearing temperatures were read by a Brown Electronik temperature indicator, as seen in Fig. 26.

A BLH SR-4 Torque Pickup type A, with a maximum torque of 5000 in.-lbf. and a maximum speed of 5000 RPM, was attached directly to the compressor shaft as shown in Fig. 27. The torque was measured by a Doric Integrating Microvoltmeter, Model DS-100, after the signal had passed through a d.c. amplifier, and a Krohn-Hite Model 3750 Filter, which are shown in Fig. 26. The calibration of the torque pickup is described in Appendix A.

The rotational speed was measured by a flux cutter located at the shaft end. The readout was displayed on the Dynasciences Electronic Counter of Fig. 28.

The barometric pressure was recorded with a Princo Fortin Mercury instrument. Gravity corrections were made according to the instruction booklet and temperature corrections were made according to Ref. 3.

V. DESIGN CONDITIONS

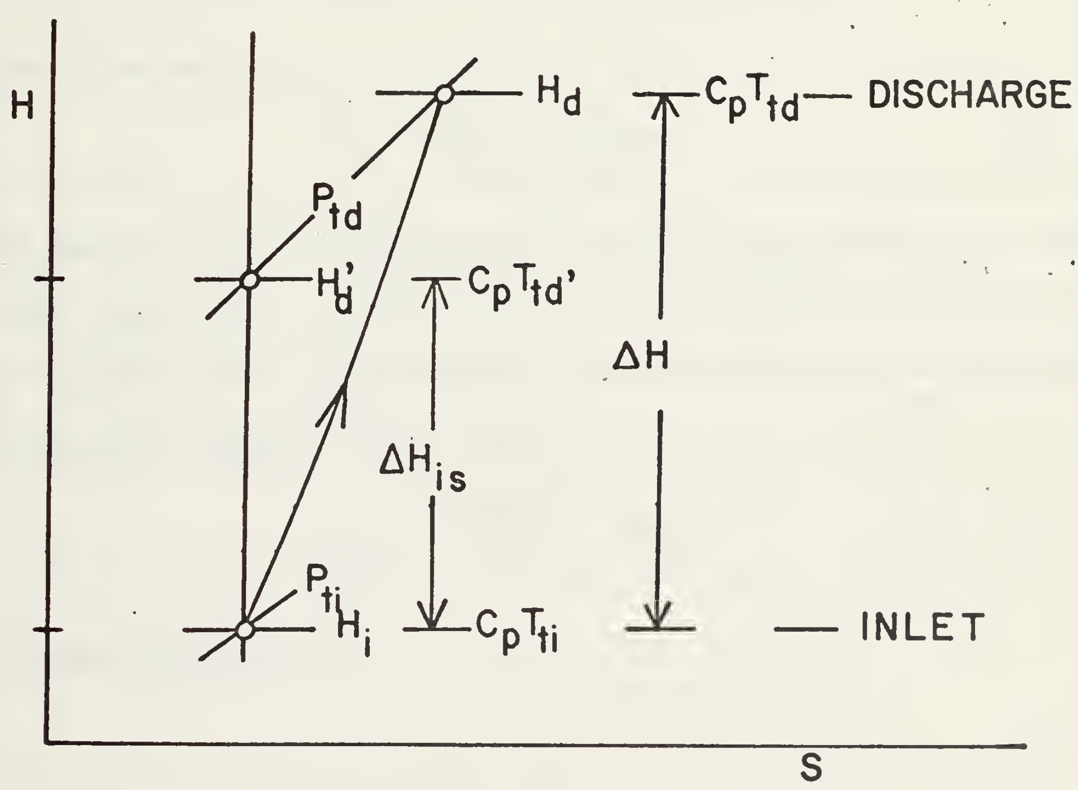
A. DERIVATION OF PERFORMANCE PARAMETERS

To determine the design point for the ONR Compressor it was necessary to establish parameters that give a measure of its performance. The performance was based on the conditions that existed at the mean radius of the compressor, 14.4 inches from the centerline. As stated in Ref. 2, the solid body blading has fifty percent reaction at the mean radius. Figs. 29 and 30 show velocity diagrams for such bladings.

The efficiency was defined as the ratio of the theoretical power P_{th} and the actual drive power P_d, or

$$\eta = \frac{P_{th}}{P_d} \tag{16}$$

The thermodynamic process through the compressor stage is represented in the figure below.



The inlet conditions are those ahead of the rotor and discharge conditions are those after the stator (see Fig. 30).

The theoretical power is

$$P_{th} = \dot{m}\ \Delta H_{is} \tag{17}$$

From the H-S diagram, assuming γ is constant,

$$P_{th} = \dot{m}\ C_p\ (T_{td}' - T_{ti})J \tag{18}$$

where T_{td}' is the discharge total temperature for an isentropic compression, and T_{ti} is the total inlet temperature. For isentropic conditions and $\Delta P_t = P_{td} - P_{ti}$ small compared with the absolute total inlet pressure P_{ti}, there is

$$T_{td}' - T_{ti} = T_{ti}\left(\frac{\gamma-1}{\gamma}\right)\frac{\Delta P_t}{P_{ti}}\ \xi \tag{19}$$

where $\xi = 1 - \dfrac{1}{2\gamma}\dfrac{\Delta P_t}{P_{ti}}$. With $C_p = \dfrac{R_G}{J} \cdot \dfrac{\gamma}{\gamma-1}$,

Equation 18 becomes

$$P_{th} = \dot{m}\ R_G\ T_{ti}\ \frac{\Delta P_t}{P_{ti}}\ \xi \tag{20}$$

The mass flow rate was determined from the pressure drop in the inlet bellmouth $\Delta p_N = P_{ta} - p_N$, where P_{ta} is the atmospheric pressure and p_N is the wall static pressure at the minimum diameter of the bellmouth. With Bernoulli's equation, Ref. 1, page 203,

$${V_{N_{th}}}^2 = \frac{2g\ R_G\ T_{ta}}{P_{ta}}\ (\Delta p_N) \tag{21}$$

The mass flow rate is

$$\dot{m}_N = \rho\ A\ V_{Nth}^{\ \ 2}\ K_B \tag{22}$$

where K_B is a blockage factor which is taken as unity for this derivation.

With Equations (21) and (22), Equation (20) is

$$P_{th} = \frac{\pi}{4} D_N^{\ 2} \sqrt{2g\ R_G \frac{T_{tA}}{P_{tA}} \Delta p_N}\ R_G \cdot T_{ti} \frac{\Delta P_t}{P_{ti}}\ \xi \tag{23}$$

The actual drive power P_d is given by

$$P_d = M \frac{\pi N}{30} \tag{24}$$

where M is the torque and N the rotational speed in RPM.

The flow coefficient φ is defined according to Ref. 1;

$$\varphi = \frac{V_a}{U} \tag{25}$$

where V_a is the average axial velocity and U the peripheral speed at the mean radius.

The work coefficient is defined as

$$\tau = \frac{\Delta H}{U^2/g} \tag{26}$$

For a constant mean radius there is from Euler's turbine equation (Ref. 1, page 259).

$$\tau = \frac{\Delta V_u}{U} \tag{27}$$

where ΔV_u is the change of the peripheral components of the absolute velocity in the rotor.

The so-called head coefficient is defined as

$$\Psi = \frac{\Delta H_{is}}{U^2/g} \tag{28}$$

From Equation (25), (26) and (27)

$$\Psi = \tau\eta$$

B. EXPERIMENTAL PROCEDURE

As described in Sections III and IV, Kiel probes were used in determining the total pressures. The static pressures were taken as the wall pressures. From Fig. 30, there is $V_3 = V_1$ at the mean radius. Hence $P_{t3} - P_{t1} = p_3 - p_1$ where P_{t3} and P_{t1} are the total pressures measured by the Kiel probe and p_1 and p_3 the wall static pressures. Therefore the performance of the stage could be based on either total or static pressure variation. The static pressure approach was used.

C. DATA REDUCTION PROGRAM

Appendix C shows a card program for the Monroe Calculator Model 1656, which determines the performance parameters from measured input data. Numerical results were obtained for twenty-one throttling configurations, with three different readings taken for each one. These data are listed in Table C-I.

D. RESULTS

The efficiency, and the work and head coefficients, are shown in Figs. 31, 32 and 33 as functions of the flow coefficient φ. The linear interdependence of τ with φ in Fig. 31 is characteristic for most axial compressors, as seen in Ref. 1, page 352. Near the surge point of the compressor the slope of the curve changes. Two configurations, wire mesh #4 and perforated plate A and wire mesh #5 and plate A, produced conditions close to surge. The efficiency and head coefficients also showed substantial changes for these configurations.

A least-squares subroutine, LSQPL2, from the IBM 360 System Library was used to determine the best slope through the data of Fig. 31.

The maximum efficiency was about 92.5 percent. The throttling configuration which produced this highest efficiency was that of wire mesh #3 and perforated plate A. Figs. 31 and 33 show that this configuration operated sufficiently far from the surge point. Hence the flow surveys were carried out for this throttling arrangement.

VI. ROTOR SURVEYS

A. SURVEY METHOD

The United Sensor 5-hole probe Type DA 120 #535 was used in the survey carriage of Fig. 20. Surveys could be made over an arc of 15° in circumferential direction and from hub to tip in radial direction.

B. DATA REDUCTION METHOD

1. Corrections for Ambient Pressure and Speed of Rotation

The surveys were made over an extended period of time at different atmospheric conditions and rotor speeds. Changes in the ambient temperature T_{ta}, and ambient pressure P_{ta}, and compressor speed N have an effect on the velocities and pressures at the survey stations. These changes are reflected in P_{tR}, the fixed reference total pressure, and p_R the reference static pressure, measured at the locations shown in Fig. 34. The quantity $q_R = P_{tR} - p_R$ is a measure of the velocity head of the flow through the compressor, even though P_{tR} and p_R were not measured at the same station.

From the test data, sample calculations shown in part 1 of Appendix D indicated that an average density change of four percent occurred in the machine. Thermodynamic relations were therefore used to calculate the velocities and densities at the survey stations. However, to apply corrections for changing values of P_{tA}, T_{tA} and N it is sufficiently accurate to assume incompressible conditions.

P_{tI} was taken as the total pressure ahead of the compressor blading at a particular radius, and P_{tD} as the total pressure downstream of the compressor blading. For a fixed throttling configuration,

the pressure drop from the ambient pressure P_{tA} to P_{tI} can be expressed by

$$P_{tA} - P_{tI} = C_I \frac{\rho}{2} V_a^2 \tag{29}$$

where V_a is the axial velocity through the blading. From the compressor discharge to the diffusor exit, where the pressure P_{tA} exists, the pressure change is

$$P_{tD} - P_{tA} = C_D \frac{\rho}{2} V_a^2 \tag{30}$$

C_I and C_D are constants for a particular blading and inlet nozzle at a fixed throttling configuration. Combining Equations (29) and (30),

$$P_{tD} - P_{tI} = (C_D + C_I) \frac{\rho}{2} V_a^2 \tag{31}$$

From Euler's turbine equation for incompressible flow

$$P_{tD} - P_{tI} = \rho U^2 \psi \tag{32}$$

where ψ is the pressure rise or head coefficient. With $\varphi = \frac{V_a}{U}$, and Equations (31) and (32)

$$\rho U^2 \psi = (C_D + C_I) \frac{\rho}{2} \varphi^2 U^2$$

It can be seen that a compressor with fixed geometry operates at the same operating point independent of P_{tA}, T_{tA} and U.

Similar to Equation (29) and assuming a perfect gas, $P_{tA} - P_{tR}$ can be expressed by

$$P_{tA} - P_{tR} = C_R \frac{P_{tA}}{2 R_G T_{tA} g} \varphi^2 U^2$$

where C_R and φ are constants. With $U = \left(\frac{\pi N}{30}\right) R$,

$$\frac{P_{tA} - P_{tR}}{P_{tA}} = K_R \left(\frac{N}{\sqrt{g\ R_G\ T_{tA}}}\right)^2 \tag{33}$$

where K_R is a constant that is not dimensionless. Since the wall reference pressure p_R is lower than P_{tR} ,

$$P_{tR} - p_R = \xi \frac{\rho}{2} V_a^2$$

since the loss in total pressure from the Kiel probe to the wall tap and the velocity head are multiples of $\frac{\rho}{2} V_a^2$.

With the equation for φ ,

$$P_{tR} - p_R = \frac{\xi}{2} \frac{P_{tA}}{R_G\ T_{tA}\ g} \varphi^2\ U^2$$

or, because φ and ξ are constants,

$$\frac{P_{tR} - p_R}{P_{tA}} = k_R \left(\frac{N}{\sqrt{g\ R_G\ T_{tA}}}\right)^2 \tag{34}$$

A similar approach can be carried out for the total pressure P_{t1} , and the static pressure p_1 , measured by the flow probe at station 1. Hence similar to Equations (33) and (34)

$$\frac{P_{tA} - P_{t1}}{P_{tA}} = K_1 \left(\frac{N}{\sqrt{g\ R_G\ T_{tA}}}\right)^2 \tag{35}$$

$$\frac{P_{t1} - p_1}{P_{tA}} = k_1 \left(\frac{N}{\sqrt{g\ R_G\ T_{tA}}}\right)^2 \tag{36}$$

If P_{tR} and p_1 are measured at the same speed N , temperature T_{tA} , and pressure P_{tA} , there is from Equations (33) and (35)

$$\frac{P_{tA} - P_{t1}}{P_{tA} - P_{tR}} = \frac{K_1}{K_R} = K = \text{constant} \tag{37}$$

The purpose of this approach was to correct the measured pressure P_{t1} to a constant average ambient pressure $(P_A)_0$. With this average pressure corresponding to an average total reference pressure $(P_{tR})_0$, an average speed N_0 and an average temperature $(T_A)_0$, the so-called corrected pressure $(P_1)_c$ that exists at $(P_A)_0$, N_0, $(T_A)_0$ is obtained. From Equation (37)

$$\frac{(P_A)_0 - (P_{t1})_c}{(P_A)_0 - (P_{tR})_0} = \frac{P_{tA} - P_{t1}}{P_{tA} - P_{tR}}$$

and rearranging,

$$(P_{t1})_c = (P_A)_0 - (P_A - P_{t1}) \left[\frac{(P_A)_0 - (P_{tR})_0}{P_{tA} - P_{tR}} \right] \tag{38}$$

In a similar manner, using Equations (34) and (36) and introducing the average static pressure $(p_R)_0$, there is

$$(P_{t1})_c - (p_1)_c = (P_{t1} - p_1) \left[\frac{(P_{tR})_0 - (p_R)_0}{P_{tR} - p_R} \right] \tag{39}$$

Since $(P_{t1})_c$ is obtained from Equation (38) the corrected static pressure at station 1 is known.

Equations (38) and (39) can also be used to establish the corrected total and static pressures at station 2 after the rotor, by replacing index 1 by index 2.

2. Performance of the Rotor

With these corrected pressures it is possible to determine the performance of the rotor.

To obtain the velocity V_1 at station 1, the total temperature T_{t1} was taken as the average ambient temperature $(T_A)_0$. Then by Fig. 36, with $C_P = R_G \, g \, \frac{\gamma}{\gamma-1}$

$$V_1^{\,2} = 2\,c_P\,(T_{t1} - T_1) = 2\,R_G\,g\,\frac{\gamma}{\gamma-1}\,T_{t1}\left[1 - \left(\frac{p_1}{P_{t1}}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

or

$$V_1{}^* = \frac{V_1}{\sqrt{g(R_G)_0\ (T_A)_0}} = \sqrt{\frac{2\gamma}{\gamma-1}\left[1 - \left(\frac{p_1}{P_{t1}}\right)^{\frac{\gamma-1}{\gamma}}\right]\cdot\frac{R_G}{(R_G)_0}} \qquad (40)$$

where $V_1{}^*$ is a dimensionless quantity. P_{t1} and p_1 are the corrected pressures, and $(R_G)_0$ is the average gas constant obtained from the average total temperature. The density ρ_1 is obtained from

$$\rho_1 = \frac{p_1}{g\ R_G\ T_1}$$

and

$$(\rho_A)_0 = \frac{(P_A)_0}{g\ (R_G)_0\ (T_A)_0}$$

Then with

$$T_{t1} = (T_A)_0\ ,$$

$$\rho_1{}^* = \frac{\rho_1}{(\rho_A)_0} = \left(\frac{p_1}{P_{t1}}\right)^{\frac{1}{\gamma}}\ \frac{P_{t1}}{(P_A)_0}\ \frac{(R_G)_0}{R_G} \qquad (41)$$

The total temperature T_{t2} after the rotor is determined from the average torque M_0 , the average speed N_0 and the average flow rate $\dot{w}$. Since $T_{t2} - T_{t1} = T_{t2} - (T_A)_0$ was small, as found in the sample calculations of Appendix D, it is sufficiently accurate to determine the flow rate $\dot{w}$ by

$$\dot{w} = \frac{\pi}{4}\,D_N^{\,2}\ \frac{(P_A)_0}{\sqrt{\frac{(R_G)_0}{g}\ (T_A)_0}}\cdot\sqrt{2\ \frac{\Delta p_N}{(P_A)_0}} \qquad (42)$$

where Δp_N is the average pressure drop in the inlet bellmouth at its smallest diameter D_N .

Then with M_0 in ft-lbf and N_0 in RPM, the actual driving power is

$$P_{drive} = M_0 \frac{\pi N_0}{30} = \dot{w}\, C_P \left(T_{t2} - (T_A)_0\right)$$

$$= \dot{w}(R_G)_0 \frac{\gamma}{\gamma-1} (T_A)_0 \left[\frac{T_{t2}}{(T_A)_0} - 1\right]$$

or

$$\frac{T_{t2}}{(T_A)_0} = 1 + \frac{M_0\ \pi N_0/30}{\dot{w}(R_G)_0 \frac{\gamma}{\gamma-1} (T_A)_0} \tag{43}$$

Then, similar to Equation (40),

$$V_2{}^* = \frac{2\gamma}{\gamma-1}\left[1 - \left(\frac{p_2}{P_{t2}}\right)^{\frac{\gamma-1}{\gamma}}\right]\frac{T_{t2}}{(T_A)_0} \cdot \frac{R_G}{(R_G)_0} \tag{44}$$

and by Equation (41)

$$\rho_2{}^* = \left(\frac{p_2}{P_{t2}}\right)^{\frac{1}{\gamma}} \frac{P_{t2}/(P_A)_0}{T_{t2}/(T_A)_0} \cdot \frac{(R_G)_0}{R_G} \tag{45}$$

Fig. 37 shows the measured pitch angle λ' and the measured yaw angle α' . The peripheral velocity $V_u{}^*$, axial velocity $V_a{}^*$ and radial velocity $V_r{}^*$ are,

$$V_a{}^* = V^* \cos \lambda' \cos \alpha'$$

$$V_r{}^* = V^* \sin \lambda'$$

$$V_u{}^* = V^* \cos \lambda' \sin \alpha'$$

and the relative velocity w* is

$$W^* = [(U^* - V_u^*)^2 + V_a^{*2} + V_r^{*2}]^{\frac{1}{2}}$$

where
$$U^* = \frac{U}{\sqrt{g(R_G)_0 \; (T_A)_0}}$$

The actual flow angles are

$$\sin \alpha = \frac{V_u^*}{V^*} = \sin \alpha' \cos \lambda'$$

$$\sin \beta = \frac{U^* - V_u^*}{w^*}$$

$$\sin \lambda = \frac{V_r^*}{V^* \cos \alpha} = \frac{\sin \lambda'}{\cos \alpha}$$

Velocities denoted with an asterisk are corrected to average ambient conditions and average rotor speed.

Because the flow properties vary in the peripheral direction, as illustrated in Fig. 39, it is necessary to obtain average values by integration. From the moment of momentum equation

$$M_a = \int_{(2)} d\dot{m}_2 \, R_2 \, V_{u2} - \int_{(1)} d\dot{m}_1 \, R_1 \, V_{u1} \tag{46}$$

where M_a is the axial moment. With $R_1 = R_2 = R$

$$\frac{M_a}{R} = \Delta\dot{m} \left[\frac{\int_{(2)} d\dot{m}_2 \, V_{u2}}{\int_{(2)} d\dot{m}_2} - \frac{\int_{(1)} d\dot{m}_1 \, V_{u1}}{\int_{(1)} d\dot{m}_1} \right] \tag{47}$$

The mass flow at a particular radius R for a differential dR , is

$$d\dot{m} = \rho \, V_a \, R d\theta dR$$

or $$\frac{d\dot{m}}{dR} = \rho\ V_a\ R\ d\theta \tag{48}$$

Equations (47) and (48) give,

$$\frac{M_a}{R} = \Delta\dot{m}\left[\frac{\int_{(2)} \rho_2 R d\theta V_{u2} V_{a2}}{\int_{(2)} \rho_2 R d\theta V_{a2}} - \frac{\int_{(1)} \rho_1 R d\theta V_{u1} V_{a1}}{\int_{(1)} \rho_1 R d\theta V_{a1}}\right]$$

With the corrected dimensionless velocities,

$$\frac{M_a}{\Delta\dot{m}} R = \left[\frac{\int_{(2)} \rho_2{}^* V_{a2}{}^* V_{u2}{}^* d\theta}{\int_{(2)} \rho_2{}^* V_{a2}{}^* d\theta} - \frac{\int_{(1)} \rho_1{}^* V_{a1}{}^* V_{u1}{}^* d\theta}{\int_{(1)} \rho_1{}^* V_{a1}{}^* d\theta}\right]\sqrt{g(R_G)_0\ (T_A)_0}$$

or $$\frac{M_a}{\Delta\dot{m}} R = \left[\overline{V}_{u2}{}^* - \overline{V}_{u1}{}^*\right]\ \sqrt{g(R_G)_0\ (T_A)_0} \tag{49}$$

where $\overline{V}_u{}^*$ are the mass averaged peripheral velocities.

The power necessary to drive the blading is

$$P_d = M_a \frac{\pi N_0}{30} = R\Delta\dot{m}\ \left[\overline{V}_{u2}{}^* - \overline{V}_{u1}{}^*\right]\ \sqrt{g(R_G)_0\ (T_A)_0}\ \cdot \frac{\pi N_0}{30}$$

From Fig. 36,

$$P = \Delta\dot{m}\ C_P\ \Delta T_W = \Delta\dot{m}\ (R_G)_0\ g\ \frac{\gamma}{\gamma-1}\ \Delta T_W \tag{50}$$

With, $$U^* = \frac{U}{\sqrt{g(R_G)_0\ (T_A)_0}} = \frac{R\pi N_0}{30} \cdot \frac{1}{\sqrt{g(R_G)_0\ (T_A)_0}}$$

Equation (50) becomes

$$\frac{\Delta T_W}{(T_A)_0} = \frac{\gamma-1}{\gamma}\ U^*\left[\overline{V}_{u2}{}^* - \overline{V}_{u1}{}^*\right] \tag{51}$$

The mass averaged total pressures at particular radii, with the corrected dimensionless velocities, are

$$\overline{P}_{t1} = \frac{\int_{(1)} \rho_1{}^* \, V_{a1}{}^* \, P_{t1} \, d\theta}{\int_{(1)} \rho_1{}^* \, V_{a1}{}^* \, d\theta} \tag{52}$$

and

$$\overline{P}_{t2} = \int_{(2)} \frac{\rho_2{}^* \, V_{a2}{}^* \, P_{t2} \, d\theta}{\rho_2{}^* \, V_{a2}{}^* \, d\theta} \tag{53}$$

With the values of $\overline{P}_{t2}$ and $\overline{P}_{t1}$ thus determined, Fig. 36 gives

$$\frac{T_{t2}{}'}{T_{t1}} = \frac{T_{t2}{}'}{(T_A)_0} = \left(\frac{\overline{P}_{t2}}{\overline{P}_{t1}}\right)^{\frac{\gamma-1}{\gamma}}$$

or

$$T_{t2}{}' = (T_A)_0 + \eta_R \, \Delta T_W$$

Rearranged,

$$\eta_R = \frac{(\overline{P}_{t2}/\overline{P}_{t1})^{\frac{\gamma-1}{\gamma}} - 1}{\frac{\gamma-1}{\gamma} \, U^* \left[\overline{V}_{u2}{}^* - \overline{V}_{u1}{}^*\right]} \tag{54}$$

This relation was used to calculate the rotor efficiency at particular radii.

C. COMPUTER PROGRAM

A computer program was set up in Fortran IV to determine the rotor efficiency with the IBM 360 Computer.

Appendix D lists the program, with computer printouts for various radial positions.

D. RESULTS

The main result of this study is shown in Fig. 38, which is a plot of the calculated rotor efficiency as a function of the radial

position. At the mean radius the efficiency is about 94 percent. Fig. 38 shows an increase of efficiency toward hub and tip. From these peaks, the efficiency drops radically toward the outer and inner walls of the channel.

The wakes of the inlet guide vanes were quite prominent ahead of the rotor. As seen in Fig. 39, they were not detected behind the rotor, since the pressure probe gives a time average of the periodic flow.

The pitch angle of the flow, and thus the radial component of the velocity, was small near the hub, but increased steadily toward the tip. At a radius of about 17.5 inches, however, the radial flow reversed itself.

Near the hub region of the blade, the axial velocity increased across the rotor, whereas it decreased near the tip region of the blade. This agrees with the test results of Ref. 2.

The peripheral component of velocity, V_{u1}, increased with increasing radius up to about 17.5 inches. This was expected since the blades were designed for forced vortex flow.

VII. CONCLUSIONS AND RECOMMENDATIONS

The radical drop of the efficiency near the hub and tip of Fig. 38 is caused by blade end and tip clearance effects. However, it is very unlikely that the actual rotor efficiency can exceed unity. It is necessary, therefore, to evaluate the effect of the assumptions that are basic to this study.

For the determination of the rotor efficiency it was assumed that the flow had cylindrical stream surfaces. The fact that the pitch angles increased towards the outer casing makes this assumption inaccurate.

The surveys were made with the 5-hole probe. Calibration tests were made to determine the true static pressure and the pitch angles. Throughout this testing it was assumed that P_{t1} was the true total pressure. At pitch angles of 20° this may not be true. The stem effects were also ignored.

It is recommended that further calibration tests be performed with the 5-hole probe to determine the effect of pitch angle on total pressure. Since pitch angles exceeded 25° in the compressor, it is necessary to cover a wider range of pitch angles in these tests.

To establish the magnitude of the tip clearance and end losses it is necessary to perform tests with increased tip clearances.

APPENDIX A (Torque Calibration)

The calibration of the torque readout instrumentation, which is shown in Figs. 26 and 27, was carried out by applying a static torque of known magnitude. This procedure consisted in hanging different weights from a twenty inch moment arm that was attached to the drive shaft, and recording the counts of the readout instrument. Table A-1 is an example of one of the three torque calibrations made. The data from these three calibrations is shown below. This curve produced a calibration constant of 17.3333 in. lbf per count.

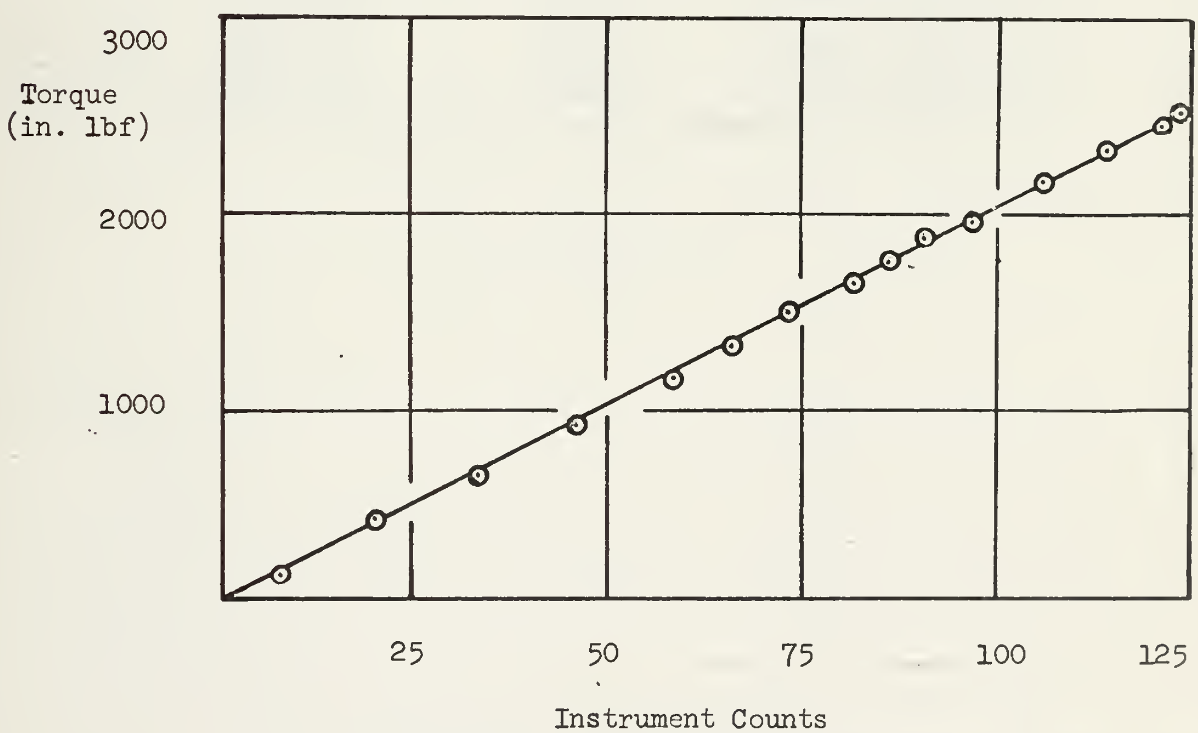


TABLE A-1

EXAMPLE OF TORQUE METER CALIBRATION

TOTAL WEIGHT LBF	APPLIED TORQUE IN-LBF	METER READING IN COUNTS	
		UP	DOWN
0	0	0	.2
8.46	169.2	7.8	8.5
20.98	419.6	20.4	21.0
33.50	670.0	33.0	33.5
46.015	920.3	45.5	46.1
58.530	1170.6	58.0	58.5
66.53	1330.6	65.9	66.4
74.53	1490.6	73.9	74.5
82.53	1650.6	81.9	82.4
87.53	1750.6	86.8	87.2
92.525	1850.5	91.7	92.2
97.525	1950.5	96.8	97.1
102.525	2050.5	101.7	102.0
107.525	2150.5	106.6	107.0
115.525	2310.5	114.6	115.0
123.525	2470.5	122.5	122.5
125.025	2500.5	123.9	123.9

APPENDIX B (Gas Constant Variation)

The gas constant R_G is defined as

$$R_G = \frac{1545.43}{M_w} \left[\frac{\text{ft-lbf}}{\text{lbm-}^\circ\text{R}}\right] \qquad \text{(B-1)}$$

where M_w is the molecular weight of the atmosphere which is a mixture of air and water.

For gas mixtures, the number of moles

$$n = \frac{\text{Amount of Constituents in lbs}}{M_w \text{ of Constituents}}$$

The molecular weight of a mixture of air and water is

$$M_w = \frac{n_a\,(28.97) + n_n\,(18)}{n_a + n_h}$$

where n_a is the number of moles of dry air, with $M = 28.97$ and n_h is the number of moles of water vapor, with $M = 18$.

$$R_G = \frac{1545.43\,(n_a + n_h)}{n_a(28.97) + n_h(18)} \qquad \text{(B-2)}$$

Using the wet and dry bulb temperature measurements, t_{dry} and t_{wet}, obtained at the compressor inlet, the relative humidity and the vapor content in grains per pound of dry air for 100 percent relative humidity is determined from a psychometric chart [Ref. 3]. With 7000 grains per pound,

$$n_h = \frac{(r)\ (\#\text{grains/lb dry air})}{7000}$$

where r is the relative humidity. Equation (B-2) is solved with the card program of Table B-1 for Monroe Calculator Model 1656.

Table B-1. R_G Determination

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PROGRAM No. I MONROE 1655 CALCULATOR
R_G DETERMINATION

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BY: J.K.W.

BR PT	ADDRESS P	COUNT	COMMAND	CODE	E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	NOTES
0	0	0	HALT	4 0 1																	Input % relative — humidy
		1	STR(0)	4 5 7																	
		2	HALT	4 0 1																	Input #grains/lbdry-air
		3	STR(1)	4 4 0																	
		4	RCL(0)	4 7 7																	
		5	x	0 7 0																	
		6	RCL(1)	4 6 0																	
		7	÷	0 7 2																	
	1	0	7	0 0 7																	
		1	0	0 0 0																	
		2	0	0 0 0																	
		3	0	0 0 0																	
		4	=	0 2 0	water vapor ; w.v.																
		5	STR(2)	4 4 1						w.v.											
		6	rcL(2)	4 6 1	w.v.																
		7	÷	0 7 2																	
1	2	0	1	0 0 1																	
		1	8	0 1 0																	
		2	=	0 2 0																	
		3	+	0 6 0																	
		4	.	0 1 2																	
		5	0	0 0 0																	
		6	3	0 0 3																	
		7	4	0 0 4																	
	3	0	5	0 0 5																	
		1	2	0 0 2																	
		2	=	0 2 0	n_a+n_H																
		3	STR(3)	4 4 2							n_a+n_H										
		4	RCL(2)	4 6 1																	
		5	+	0 6 0																	
		6	1	0 0 1																	
		7	=	0 2 0																	

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Table B-1 (CONT.)

BR PT	ADDRESS P	COUNT	COMMAND	CODE	E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	NOTES
2	4	0	STR(4)	4 4 3																	
		1	1	0 0 1																	
		2	5	0 0 5																	
		3	4	0 0 4																	
		4	5	0 0 5																	
		5	.	0 1 2																	
		6	4	0 0 4																	
		7	3	0 0 3																	
	5	0	×	0 7 0																	
		1	RCL(3)	4 6 2	$n_a + n_H$																
		2	=	0 2 0																	
		3	÷	0 7 2																	
		4	RCL(4)	4 6 3																	
		5	=	0 2 0	R_G																
		6	HALT	4 0 1																	Read R_G on display
		7																			
		0																			
		1																			
		2																			
		3																			
		4																			
		5																			
		6																			
		7																			
		0																			
		1																			
		2																			
		3																			
		4																			
		5																			
		6																			
		7																			

APPENDIX C (Mean Radius Compressor Performance Program)

The performance parameters of Section VI are calculated on a Monroe 1656 calculator with the program of Table C-3.

The input parameters are:

P_{tA}	Atmospheric Pressure (in. Hg.)
$P_{tA}-P_{encl.}$	Pressure drop across enclosure to inlet (in. H_2O)
T_{ti}	Total inlet temperature (^oR)
R_G	Gas Constant $\left(\frac{ft\text{-}lbf}{lbm\text{-}^oR}\right)$
Δp_N	Pressure drop across inlet nozzle (in. H_2O)
ΔP_t or Δp_s	Pressure rise across stage (in. H_2O)
P_A-P_{k3}' or P_A-P_{s3}	Pressure difference just ahead of the rotor (in. H_2O)
Counts	Torque counts
RPM	Compressor Speed (RPM)

With these inputs, the parameters Φ , τ , η and Ψ are calculated. To find the design point, 21 throttling configurations were tested. The results are listed in Table C-1. The dimensions of the wire mesh screens and perforated plates are listed in Table C-2.

Table C-1. Flow Parameters for Various Throttling Configurations

THROTTLE ARRANGEMENT	φ	τ	η	$\dot{m}$	Ψ
None	.61830	.17787	.77148	1.93220	.13721
None	.61939	.17268	.78220	1.93220	.13507
None	.61663	.17396	.77535	1.92382	.13488
A+2	.48049	.33074	.91163	1.42964	.30151
A+2	.48449	.33012	.91771	1.43572	.30296
A+2	.48312	.32807	.92691	1.42958	.30409
A+3	.47315	.33873	.92545	1.38249	.31348
A+3	.47279	.33854	.92015	1.38355	.31150
A+3	.46236	.34726	.90142	1.34691	.31302
A+4	.42514	.37847	.80375	1.26418	.30419
A+4	.42156	.38048	.79681	1.25100	.30317
A+4	.42386	.37648	.81110	1.24969	.30536
A+5	.41617	.37921	.77474	1.21943	.29379
A+5	.42296	.37634	.78127	1.23153	.29403
A+5	.42416	.37347	.78361	1.22630	.29265
1+4	.54164	.25378	.86001	1.64931	.21826
1+4	.54825	.24897	.87814	1.66809	.21863
1+4	.53780	.25344	.86435	1.63384	.21906
1+5	.54135	.25270	.89839	1.61868	.22703
1+5	.54337	.25335	.89702	1.61868	.22726
1+5	.53328	.26098	.86718	1.59156	.22631
5	.55164	.24504	.87065	1.64658	.21334
5	.55462	.24165	.88627	1.64620	.21417
5	.54500	.24869	.85960	1.61838	.21377

Table C-1 (CONT.)

THROTTLE ARRANGEMENT	φ	τ	η	$\dot{m}$	Ψ
2+3	.56156	.23084	.84478	1.67247	.19501
2+3	.55730	.23273	.83026	1.65531	.19322
2+3	.56012	.22970	.83913	1.65930	.19274
2+4	.54521	.25638	.90329	1.58560	.23159
2+4	.530032	.26761	.85717	1.53913	.22939
2+4	.53660	.25978	.89111	1.55118	.23149
2+5	.52411	.27509	.87573	1.50027	.24091
2+5	.53079	.27108	.89125	1.51174	.241600
2+5	.52496	.27603	.87888	1.48789	.24260
3+4	.51884	.28179	.88284	1.53002	.24877
3+4	.51699	.28097	.87422	1.51614	.24563
3+4	.51965	.28289	.87196	1.51612	.24667
3+5	.51494	.29157	.87652	1.48022	.25557
3+5	.52308	.28986	.88260	1.49383	.25583
3+5	.52541	.28589	.89187	1.49358	.25498
4+5	.50847	.30921	.92834	1.42320	.28705
4+5	.49158	.31626	.89991	1.36633	.28460
4+5	.49355	.31792	.90238	1.36622	.28689
1+4+5	.48250	.32584	.90695	1.32988	.29552
1+4+5	.47845	.33431	.86998	1.31417	.29084
1+4+5	.48585	.33522	.89000	1.31650	.29834
A	.48231	.32478	.89233	1.44871	.28981
A	.48286	.32580	.89848	1.42802	.29272
A	.48151	.33259	.87674	1.41678	.29159
2+3+5	.49213	.31185	.91446	1.43347	.28517
2+3+5	.49049	.32238	.89058	1.41027	.28711
2+3+5	.48856	.32002	.90405	1.39578	.28931

Table C-1 (CONT.)

THROTTLE ARRANGEMENT	φ	τ	η	$\dot{m}$	Ψ
A+1	.47497	.33611	.90737	1.38086	.30498
A+1	.48003	.33728	.90110	1.37941	.30393
A+1	.47725	.33559	.89492	1.36811	.30033
1+2	.57762	.21485	.79679	1.72295	.17119
1+2	.57678	.213070	.80771	1.72468	.17210
1+2	.57939	.21257	.80476	1.72944	.17107
1+3	.56405	.22326	.82732	1.67981	.18471
1+3	.56718	.22458	.82970	1.67899	.18633
1+3	.56704	.22522	.81660	1.67672	.18392
2+3	.55345	.23566	.88304	1.61304	.20810
2+3	.55716	.24472	.85392	1.61378	.20897
2+3	.54841	.24517	.84345	1.58520	.20679

TABLE C-2

THROTTLING MEMBRANES

(1) SCREENS

	1	2	3	4	5
Mesh Number (IN^{-1})	4	10	12	12	12
Wire Dia. ($\frac{1}{1000}$ IN)	28	16	18	25	28

(2) PERFORATED PLATES

	A	B	C
Hole Dia. (IN)	3/4	5/8	1/4
Spacing (IN)	1	7/8	3/8

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Table C-3. Mean Radius Compressor Performance

ADDRESS	P COUNT	COMMAND	CODE	E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	NOTES
0	0	HALT	401	P_a(Hg.)																Input Atm. Press. P_a
	1	X	070																	
	2	1	001																	
	3	3	003																	
	4	.	012																	
	5	6	006																	
	6	=	020																	
	7	STR(0)	457	P_A (in. H_2O)			P_A													
1	0	HALT	401					$P_A - P_{end}$												Input $P_A - P_{end}$ (in. H_2O)
	1	STR(1)	440																	
	2	CHG. SIN.	013																	
	3	+	060																	
	4	RCL(0)	477	P_A																
	5	=	020																	
	6	STR(0)	457				P_{end}													
	7	x	070																	
2	0	.	012																	
	1	1	001																	
	2	6	006																	
	3	1	001																	
	4	4	004																	
	5	9	011																	
	6	0	000																	
	7	7	007																	
3	0	÷	072																	
	1	HALT	401	T_{ti}																Input T_{ti} (°R)
	2	÷	072																	
	3	HALT	401	R_G																Input R_G
	4	=	020	ρ																
	5	STR(2)	441						ρ (slug/ft^3)											
	6	HALT	401	Δp_w																Input Δp_w (in. H_2O)
	7	−	062																	

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Table C-3 (CONT.)

ADDRESS	P COUNT	COMMAND	CODE	E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	NOTES
4	0	RCL(1)	460	P_{end}			P_e	P_A-P_e	ρ											
	1	=	020																	
	2	X	070																	
	3	RCL(2)	461	ρ																
	4	=	020																	
	5	$\sqrt{}$	056																	
	6	X	070																	
	7	2	002																	
5	0	2	002																	
	1	.	012																	
	2	4	004																	
	3	7	007																	
	4	9	011																	
	5	9	011																	
	6	=	020	$\dot{w}$																
	7	STR(3)	442							$\dot{w}$ (slug/sec)										
6	0	HALT	401																	Input Δp (in. H_2O)
	1	STR(4)	443	Δp							Δp									
	2	HALT	401																	Input P_A-P_{S3} (in. H_2O)
	3	CHG. SIN.	013																	
	4	+	060																	
	5	RCL(1)	460	P_A-P_e																
	6	+	060																	
	7	RCL(0)	477	P_e																
7	0	=	020																	
	1	STR(5)	444	p_s								p_s inlet								
	2	RCL(4)	463	Δp																
	3	÷	072																	
	4	RCL(5)	464	p_s																
	5	÷	072																	
	6	2	002																	
	7	.	012																	

Table C-3 (CONT.)

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ADDRESS P COUNT			COMMAND	CODE	REGISTERS E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	NOTES
	8	0	8	010				P_e	P_t-P_e	ρ	$\dot{W}$	Δp	p_{si}								
		1	=	020																	
		2	CHG.SIN.	013																	
		3	+	060																	
		4	1	001																	
		5	=	020	[illegible]									[illegible]							
		6	STR(6)	445																	
		7	RCL(4)	463	Δp																
	9	0	X	070																	
		1	RCL(3)	462	$\dot{W}$																
		2	÷	072																	
		3	RCL(2)	461	ρ																
		4	X	070																	
		5	RCL(6)	465	[illegible]																
		6	X	070																	
		7	.	012																	
1	0	0	0	000																	
		1	0	000																	
		2	9	011																	
		3	4	004																	
		4	5	005																	
		5	5	005																	
		6	X	070																	
		7	RCL(0)	477	P_e																
1	1	0	÷	072																	
		1	RCL(5)	464	p_{si}																
		2	=	020																	
		3	STR(5)	444	P_{ch}									P_{ch}								
		4	HALT	401																	Input Torque counts
		5	X	070																	
		6	.	012																	
		7	0	000																	

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Table C-3 (CONT.)

ADDRESS P COUNT	COMMAND	CODE	E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	NOTES
1 2 0	0	0 0 0				P_e	P_t-P_e	ρ	$\dot{W}$	Δp	~~P_{th}~~ P_{th}	ϵ							
1	0	0 0 0																	
2	3	0 0 3																	
3	1	0 0 1																	
4	3	0 0 3																	
5	2	0 0 2																	
6	X	0 7 0																	
7	HALT	4 0 1																	Input RPM
1 3 0	STR(6)	4 4 5	N									N							
1	=	0 2 0																	
2	STR(1)	4 4 0	P				P												
3	RCL(5)	4 6 4	P_{th}																
4	÷	0 7 2																	
5	RCL(1)	4 6 0	P																
6	=	0 2 0																	
7	STR(0)	4 5 7	η			η													
1 4 0	RCL(4)	4 6 3	Δp																
1	÷	0 7 2																	
2	RCL(2)	4 6 1	ρ																
3	÷	0 7 2																	
4	RCL(6)	4 6 5	N																
5	X	0 7 0																	
6	3	0 0 3																	
7	2	0 0 2																	
1 5 0	9	0 1 1																	
1	.	0 1 2																	
2	2	0 0 2																	
3	9	0 1 1																	
4	4	0 0 4																	
5	=	0 2 0	ψ							ψ									
6	STR(4)	4 4 3																	
7	HALT	4 0 1																	PUNCH RESUME
			E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	

Table C-3 (CONT.)

ADDRESS P COUNT			COMMAND	CODE	REGISTERS E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	NOTES
0	0	0	RCL(3)	4 6 2	$\dot{w}$			η	P	ρ	$\dot{W}$	γ	P_{th}	N							
		1	÷	0 7 2																	
		2	RCL(2)	4 6 1	ρ																
		3	÷	0 7 2																	
		4	RCL(6)	4 6 5	N																
		5	×	0 7 0																	
		6	1	0 0 1																	
		7	.	0 1 2																	
	1	0	7	0 0 7																	
		1	5	0 0 5																	
		2	9	0 1 1																	
		3	0	0 0 0																	
		4	5	0 0 5																	
		5	=	0 2 0	φ									φ							
		6	STR(6)	4 4 5																	
		7	RCL(4)	4 6 3	γ																
	2	0	÷	0 7 2																	
		1	RCL(0)	4 7 7	η																
		2	=	0 2 0																	
		3	HALT	4 0 1	↑																Read ↑ on display
		4																			
		5																			
		6																			
		7																			
		0																			
		1																			
		2																			
		3																			
		4																			
		5																			
		6																			
		7																			
					E	A	M	0	1	2	3	4	5	6	7	8	9	X	Y	Z	

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APPENDIX D (Data Reduction Program for Rotor Surveys)

A. SAMPLE CALCULATIONS

1. Density Changes

Reference 4 shows, that for one stage operation, the pressure rise is about 12 in. H_2O, for a volume flow rate $\mathcal{VF}$ of 1000 $ft^3/sec.$ and a drive power of 135 H.P. At $P_{tA} = 14.7$ psia and $T_{tA} = 520^{o}R$, the weight flow $\dot{w}$ is

$$\dot{w} = \mathcal{VF}\,\rho$$

$$= \underline{76.3 \text{ lbm/sec}}$$

Then the maximum possible temperature rise of the air is, with $C_P = .24 \frac{Btu}{lbm} {}^{o}R$,

$$\Delta T_t = \frac{P_d}{JC_P\dot{w}}$$

$$= \underline{5.2^{o}R}$$

The average axial velocity at station 1 of Fig. (34) is

$$V_a = \frac{\mathcal{VF}}{A} = \underline{221 \text{ ft/sec}}$$

For flow angle $\alpha_1 = 25^{o}$,

$$V_1 = \frac{V_a}{\cos\alpha_1} = \underline{243 \text{ ft/sec}}$$

For an isentropic expansion from P_{tR} , T_{tA} to p_1 , T_1

$$\frac{V_1^{\,2}}{2gJC_P} = T_{ta} - T_1$$

or

$$\underline{\frac{T_1}{T_{tA}} = 0.9906}$$

and for $\gamma = 1.4$,

$$\frac{p_1}{P_{tR}} = 0.9673$$

The survey tests were carried out at an average P_{tR} of 14.41 psia.

Hence

$$\frac{\rho_1}{\rho_a} = \frac{p_1}{P_{tA}} \cdot \frac{T_{ta}}{T_1} = \underline{\underline{0.9572}}$$

After the rotor the average total pressure P_{t2} is 14.84 psia. Since $V_{a1} = V_{a2}$ and assuming $\alpha_2 = 40^\circ$,

$$V_2 = \frac{V_{a2}}{\cos \alpha_2} = 288 \text{ ft/sec}$$

and

$$\frac{T_2}{T_{t2}} = 0.9869$$

$$\frac{P_2}{P_{t2}} = 0.9548$$

therefore

$$\frac{\rho_2}{\rho_a} = \underline{\underline{0.9670}}$$

B. DATA REDUCTION PROGRAM

The data reduction method developed in Section VI is performed by the IBM 360 Computer. Measured pressures and temperatures are corrected for average conditions. The program is listed in Table D-1. The velocities ahead of and after the rotor, together with the rotor efficiency for several radial positions, are listed in Tables D-2 to D-15.

1. <u>Data Input</u>

Data are read in as follows, first for the condition ahead of and then for those after the rotor.

FORTRAN NAME			
AHEAD OF ROTOR	AFTER ROTOR	FORMAT	DESCRIPTION
N1	N2	I2	Number of Positions Surveyed in Circumferential Direction
PAHG	PAHG2	F10.5	Atmospheric Pressure (in. Hg.)
T	T2	F10.5	Temperature used in correcting atmospheric pressure (^{o}F)
DELPIR	DLPIR2	F10.5	Pressure difference $P_{t1}-p_R$ (in. H_2O)
DELPAR	DLPAR2	F10.5	$P_{tA}-p_R$ (in. H_2O)
DELP12	DLP122	F10.5	$P_{t1}-p_1$ (in. H_2O)
DELPN	DLPN2	F10.5	Δp_N (in. H_2O)
DELK3A	DLK3A2	F10.5	P_{tA} - Kiel total pressure ahead of rotor (in. H_2O)
DELKIA	DLKIA2	F10.5	P_{tA} - Kiel total pressure ahead of IGV (= P_{tR}) (in. H_2O)
DELK5A	DLK5A2	F10.5	P_{tA} - Kiel total pressure after rotor (in. H_2O)
DELS3A	DLS3A2	F10.5	P_{tA} - static wall pressure at rotor (= p_R) (in. H_2O)
DELPAE	DLPAE2	F10.5	P_{tA} - $P_{enclosure}$ (in. H_2O)
RG	RG2	F10.5	Gas Constant $(\frac{ft\text{-}lbf}{lbm\text{-}^{o}R})$
TT1	TT2	F10.5	Ambient Total Temperature, T_{tA} (^{o}F)
DTHETA	THETA2	F10.5	$d\theta$, used in integration (^{o})
ALPH1	ALPH2	F10.5	Yaw Angle α (^{o})
RPM	RPM2	F10.5	Rotor Speed (RPM)
TORQ	TORQ2	F10.5	Torque (counts)
MR	MR2	F10.5	$M_r = \frac{P_1-P_2}{P_1}$
MT	MT2	F10.5	P_4 - P_5 (in. H_2O)
PER1	PER2	F10.5	Circumferential position θ (^{o})

D-1. Listing of Rotor Performance Program

```
C   *************************************************
C
C   ***** FORTRAN IV COMPUTER PROGRAM DEVELOPED      *****
C   ***** ACCORDING TO THE DATA REDUCTION METHOD     *****
C   ***** CONTAINED IN SECTION VI. THIS METHOD       *****
C   ***** WILL BE USED IN FUTURE EXPERIMENTAL        *****
C   ***** INVESTIGATIONS OF TIP CLEARANCE EFFECTS    *****
C   ***** ON AXIAL COMPRESSOR PERFORMANCE.           *****
C
C   *************************************************
      IMPLICIT REAL*8(A-H,K,L,M,O-Z)
C *****  PHYSICAL CONSTANTS
      CN=35.75
      PI=3.14159265D0
C *****  REFERENCE VALUES
      PAC=14.67039600
      PSRC=14.151090D0
      PTRC=14.380090D0
      PNREF=.07416296600
      RGC=53.4745D0
      TAC=515.0D0
      RPMC=2315.0D0
      TCRQ0=158.744D0
C *****  GAMMA
      GAM=1.4
      GAM1=(GAM-1)/GAM
      GAMM=1/GAM
      GAMM1=GAM/(GAM-1)
C *****  DIMENSION STATEMENTS
      DIMENSION CFHG(50),CFHG2(50),CFH2C(50),CFH2C2(50),
     1PAHG(50),PAHG2(50),PAPSI(50),PAPSI2(50),P1PSI(50),
     2P1PSI2(50),PSPSI(50),PSPSI2(50),PRPSI(50),PRPSI2(50),
     3DPNPSI(50),PNPSI2(50),PK3(50),PK32(50),PK1(50)
      DIMENSION PK12(50),PK5(50),PK52(50),DELPAE(50),
     1DLPAE2(50),PS3(50),PS32(50),X(50),X1(50),Y(50),
     2Y1(50),V(50),V1(50),W(50),W1(50),P(50),P1(50),
     3R(50),R1(50),S(50),S1(50),Q(50),Q1(50)
      DIMENSION VI(50),V2(50),PS1(50),PS2(50),PT1(50),
     1PT2(50),RG(50),RG2(50),RHO1(50),RHO2(50),
     2DELPN(50), DLPN2(50),VA1(50),VA2(50),LAM(99),LAM2(99),
     3ALPH1(99),ALPH2(99),VU1(50),VU2(50),VR1(50),VR2(50)
      DIMENSION WI(50),W2(50),T(50),T2(50),TT1(50),TT2(50),
     1DELP1R(50),DLP1R2(50),DELPAR(50),DLPAR2(50),DELP12(50),
     2DLP122(50),DELK3A(50),DLK3A2(50),DELK1A(50),DLK1A2(50)
      DIMENSION  DELK5A(50),DLK5A2(50),DELS3A(50),DLS3A2(50),
     1DTHETA(50),THETA2(50), RPM(50),
     2RPM2(50),TORQ(50),TORQ2(50),MR(50),MR2(50),KQ(50),
     3KQ2(50)
```

D-1 (CONT.)

```
      DIMENSION P45(50),P452(50),MT(50),MT2(50)
      DIMENSION VUV(50),ACTAL(50),VUV2(50),ACTAL2(50),
     1BETA(50),BETA2(50),ACBTA(50),ACBTA2(50),VRV(50),
     2VRV2(50),ACTLAM(50),ACLAM2(50)
      DIMENSION PER1(50),PER2(50),
     1SV1(50),SV2(50),SPER1(50),SPER2(50)
      DIMENSION RANGE(10)
C *****  DATA INPUT
      READ(5,12) N1
      READ(5,22) (PAHG(I),I=1,N1)
      READ(5,22) (T(I),I=1,N1)
      READ(5,22) (DELP1R(I),I=1,N1)
      READ(5,22) (DELPAR(I),I=1,N1)
      READ(5,22) (DELP12(I),I=1,N1)
      READ(5,22) (DELPN(I),I=1,N1)
      READ(5,22) (DELK3A(I),I=1,N1)
      READ(5,22) (DELK1A(I),I=1,N1)
      READ(5,22) (DELK5A(I),I=1,N1)
      READ(5,22) (DELS3A(I),I=1,N1)
      READ(5,22) (DELPAE(I),I=1,N1)
      READ(5,22) (RG(I),I=1,N1)
      READ(5,22) (TT1(I),I=1,N1)
      READ(5,22) (DTHETA(I),I=1,N1)
      READ(5,22) (ALPH1(I),I=1,N1)
      READ(5,22) (RPM(I),I=1,N1)
      READ(5,22) (TORQ(I),I=1,N1)
      READ(5,22) (MR(I),I=1,N1)
      READ(5,22) (MT(I),I=1,N1)
      READ(5,22) (PER1(I),I=1,N1)
      READ(5,12) N2
      READ(5,22) (PAHG2(I),I=1,N2)
      READ(5,22) (T2(I),I=1,N2)
      READ(5,22) (DLP1R2(I),I=1,N2)
      READ(5,22)(DLPAR2(I),I=1,N2)
      READ(5,22) (DLP122(I),I=1,N2)
      READ(5,22) (DLPN2(I),I=1,N2)
      READ(5,22) (DLK3A2(I),I=1,N2)
      READ(5,22) (DLK1A2(I),I=1,N2)
      READ(5,22)(DLK5A2(I),I=1,N2)
      READ(5,22) (DLS3A2(I),I=1,N2)
      READ(5,22) (DLPAE2(I),I=1,N2)
      READ(5,22) (RG2(I),I=1,N2)
      READ(5,22) (TT2(I),I=1,N2)
      READ(5,22) (THETA2(I),I=1,N2)
      READ(5,22) (ALPH2(I),I=1,N2)
      READ(5,22) (RPM2(I),I=1,N2)
      READ(5,22) (TORQ2(I),I=1,N2)
      READ(5,22) (MR2(I),I=1,N2)
```

D-1 (CONT.)

```
      READ(5,22) (MT2(I),I=1,N2)
      READ(5,22) (PER2(I),I=1,N2)
   12 FORMAT(I2)
   22 FORMAT(5F10.5)
      DO 102 I=1,N1
      TORQ(I)=TORQ(I)/12*17.3333
      MT(I)=MT(I)/DELP12(I)
  102 CONTINUE
      DO 105 I=1,N2
      TORQ2(I)=TORQ2(I)/12*17.3333
      MT2(I)=MT2(I)/DLP122(I)
  105 CONTINUE
C DATA FOR DETERMINATION OF KG
      DO 80 I=1,N1
      IF(MR(I).GE..05) GO TO 81
      IF(MR(I).GE..04) GO TO 82
      IF(MR(I).GE..035) GO TO 83
      IF(MR(I).GE..03) GO  TO 84
      IF(MR(I).GE..0235) GO TO 85
      IF(MR(I).GE..0175) GO TO 86
      IF(MR(I).GE..0145) GO TO 87
      IF(MR(I).GE..01) GO TO 88
      IF(MR(I).LT..01) GO TO 89
   81 KG(I)=1.040
      GO TO 80
   82 KG(I)=1.035
      GO TO 80
   83 KG(I)=1.03
      GO TO 80
   84 KG(I)=1.025
      GO TO 80
   85 KG(I)=1.0125
      GO TO 80
   86 KG(I)=1.005
      GO TO 80
   87 KG(I)=1.0
      GO TO 80
   88 KG(I)=.9950
      GO TO 80
   89 KG(I)=.99
   80 CONTINUE
      DO 90 I=1,N2
      IF(MR2(I).GE..05) GO TO 71
      IF(MR2(I).GE..04) GO TO 72
      IF(MR2(I).GE..035) GO TO 73
      IF(MR2(I).GE..03) GO TO 74
      IF(MR2(I).GE..0235) GO TO 75
      IF(MR2(I).GE..0175) GO TO 76
```

```
      IF(MR2(I).GE..0145) GO TO 77
      IF(MR2(I).GE..01) GC TO 78
      IF(MR2(I).LT..01) GC TO 79
   71 KG2(I)=1.040
      GC TO 9C
   72 KG2(I)=1.035
      GC TO 90
   73 KG2(I)=1.03
      GC TO 90
   74 KG2(I)=1.025
      GC TO 9C
   75 KG2(I)=1.0125
      GC TO 90
   76 KG2(I)=1.005
      GC TO 90
   77 KG2(I)=1.0
      GC TO 9C
   78 KG2(I)=.9950
      GC TO 9C
   79 KG2(I)=.99
   9C CCNTINUE
C **** CETERMINATION OF PITCH ANGLE LAMECA FROM
C       CALIBRATION CURVES FOR UNITED SENSOR PRCEE
C       CA-120-535
      DC 900 I=1,N1
      IF(MT(I).GT..1) GO TO 881
      IF(MT(I).GT..06) GC TO 882
      IF(MT(I).GT..03) GC TO 883
      IF(MT(I).GT..00) GC TO 884
      IF(MT(I).GT.-.01) GO TO 885
      IF(MT(I).GT.-.02) GC TC 886
      IF(MT(I).GT.-.03) GC TC 887
      IF(MT(I).GT.-.04) GC TO 888
      IF(MT(I).GT.-.05) GC TC 889
      IF(MT(I).GT.-.06) GC TC 890
      IF(MT(I).GT.-.07) GC TC 891
      IF(MT(I).GT.-.10) GC TC 892
      IF(MT(I).GT.-.12) GO TO 893
      IF(MT(I).GT.-.14) GC TO 894
      IF(MT(I).GT.-.16) GC TO 895
      IF(MT(I).GT.-.18) GC TO 896
      IF(MT(I).LE.-.18) GC TC 897
  881 LAM(I)=10.0
      GC TO 900
  882 LAM(I)=9.0
      GC TO 900
  883 LAM(I)=7.5
      GC TO 900
```

D-1 (CONT.)

```
884 LAM(I)=6.5
    GO TO 900
885 LAM(I)=5.0
    GO TO 900
886 LAM(I)=3.0
    GO TO 900
887 LAM(I)=1.5
    GO TO 900
888 LAM(I)=0.0
    GO TO 900
889 LAM(I)=-1.5
    GO TO 900
890 LAM(I)=-2.0
    GO TO 900
891 LAM(I)=-3.0
    GO TO 900
892 LAM(I)=-5.0
    GO TO 900
893 LAM(I)=-6.0
    GO TO 900
894 LAM(I)=-7.0
    GO TO 900
895 LAM(I)=-8.0
    GO TO 900
896 LAM(I)=-8.5
    GO TO 900
897 LAM(I)=-10.0
900 CONTINUE
    DO 999 I=1,N2
    IF(MT2(I).GT..10) GO TO 981
    IF(MT2(I).GT..06) GO TO 982
    IF(MT2(I).GT..03) GO TO 983
    IF(MT2(I).GT..00) GO TO 984
    IF(MT2(I).GT.-.01) GO TO 985
    IF(MT2(I).GT.-.02) GO TO 986
    IF(MT2(I).GT.-.03) GO TO 987
    IF(MT2(I).GT.-.04) GO TO 988
    IF(MT2(I).GT.-.05) GO TO 989
    IF(MT2(I).GT.-.06) GO TO 990
    IF(MT2(I).GT.-.07) GO TO 991
    IF(MT2(I).GT.-.10) GO TO 992
    IF(MT2(I).GT.-.12) GO TO 993
    IF(MT2(I).GT.-.14) GO TO 994
    IF(MT2(I).GT.-.16) GO TO 995
    IF(MT2(I).GT.-.18) GO TO 996
    IF(MT2(I).LE.-.18) GO TO 997
981 LAM2(I)=10.0
    GO TO 999
```

D-1 (CONT.)

```
  982 LAM2(I)=9.0
      GO TO 999
  983 LAM2(I)=7.5
      GO TO 999
  984 LAM2(I)=6.5
      GO TO 999
  985 LAM2(I)=5.0
      GO TO 999
  986 LAM2(I)=3.0
      GO TO 999
  987 LAM2(I)=1.5
      GO TO 999
  988 LAM2(I)=0.0
      GO TO 999
  989 LAM2(I)=-1.5
      GO TO 999
  990 LAM2(I)=-2.0
      GO TO 999
  991 LAM2(I)=-3.0
      GO TO 999
  992 LAM2(I)=-5.0
      GO TO 999
  993 LAM2(I)=-6.0
      GO TO 999
  994 LAM2(I)=-7.0
      GO TO 999
  995 LAM2(I)=-8.0
      GO TO 999
  996 LAM2(I)=-8.5
      GO TO 999
  997 LAM2(I)=-10.0
  999 CONTINUE
C *****  CONVERSION OF PRESSURES TO PSIA
      DO 20 I=1,N1
      ALPH1(I)=ALPH1(I)*PI/180.0
      LAM(I)=LAM(I)*PI/180.0
      DTHETA(I)=DTHETA(I)*PI/180
      CFHG(I)=(13.63905-.0013630303*T(I))*0.4891585/13.54
      CFH2O(I)=(.99837633+1.0605756E-04*T(I)-1.5931861E-06*
     1T(I)*T(I))*.03612692
      PAHG(I)=PAHG(I)-.023
      PAPSI(I)=PAHG(I)*CFHG(I)
      PIPSI(I)=(DELP1R(I)-DELPAR(I))*CFH2O(I)+PAPSI(I)
      PSPSI(I)=((DELP1R(I)-DELPAR(I))*CFH2O(I)+PAPSI(I)-(KQ
     1(I)*DELP12(I)*CFH2O(I)))
      PRPSI(I)=(-DELPAR(I)*CFH2O(I))+PAPSI(I)
      DPNPSI(I)=DELPN(I)*CFH2O(I)
      PK3(I)=-DELK3A(I)*CFH2O(I)+PAPSI(I)
```

```
      PK1(I)=-DELK1A(I)*CFH2O(I)+PAPSI(I)
      PK5(I)=-DELK5A(I)*CFH2O(I)+PAPSI(I)
      DELPAE(I)=DELPAE(I)*CFH2O(I)
      PS3(I)=-DELS3A(I)*CFH2O(I)+PAPSI(I)
      DPNPSI(I)=DPNPSI(I)+DELPAE(I)
   20 CONTINUE
      DO 21 I=1,N2
    1 FORMAT(10X,2F10.5)
      ALPH2(I)=ALPH2(I)*PI/180.0
      THETA2(I)=THETA2(I)*PI/180
      LAM2(I)=LAM2(I)*PI/180.0
      CFHG2(I)=(13.63905-.0013630303*T2(I))*0.4891585/13.54
      CFH2O2(I)=(.99837633+1.0605756E-04*T2(I)-1.5931861E-06
     1*T2(I)*T2(I))*.03612692
      PAHG2(I)=PAHG2(I)-.023
      PAPSI2(I)=PAHG2(I)*CFHG2(I)
      P1PSI2(I)=(DLP1R2(I)-DLPAR2(I))*CFH2O2(I)+PAPSI2(I)
      PSPSI2(I)=((DLP1R2(I)-DLPAR2(I))*CFH2O2(I)+PAPSI2(I)
     1-(KQ2(I)*DLP122(I)*CFH2O2(I)))
      PRPSI2(I)=-(DLPAR2(I)*CFH2O2(I))+PAPSI2(I)
      PNPSI2(I)=DLPN2(I)*CFH2O2(I)
      PK32(I)=-DLK3A2(I)*CFH2O2(I)+PAPSI2(I)
      PK12(I)=-DLK1A2(I)*CFH2O2(I)+PAPSI2(I)
      DLPAE2(I)=DLPAE2(I)*CFH2O2(I)
      PK52(I)=-DLK5A2(I)*CFH2O2(I)+PAPSI2(I)
      PS32(I)=-DLS3A2(I)*CFH2O2(I)+PAPSI2(I)
      PNPSI2(I)=PNPSI2(I)+DLPAE2(I)
   21 CONTINUE
C *****  DETERMINATION OF CORRECTED TOTAL AND STATIC PRESS-
C           URE FROM REFERENCE PRESSURES
      DO 63 I=1,N1
      PT1(I)=PAO-PAO*((PAPSI(I)-P1PSI(I))/(PAPSI(I)-PK1(I))*
     1(1-PTRO/PAO))
      PS1(I)=PT1(I)-((P1PSI(I)-PSPSI(I))*((PTRO-PSRO)/(PK1(I
     1)-PS3(I))))
   63 CONTINUE
      DO 33 I=1,N2
      PT2(I)=PAO-PAO*((PAPSI2(I)-P1PSI2(I))/(PAPSI2(I)-PK12(
     1I))*(1-PTRO/PAO))
      PS2(I)=PT2(I)-((P1PSI2(I)-PSPSI2(I))*((PTRO-PSRO)/(PK1
     12(I)-PS32(I))))
   33 CONTINUE
C *****  PERIPHERAL SPEED USTAR
      U=   PI*RPMO/30*RADIUS/((32.174*RGC*TAO)**0.5)/12.0
      WRITE(6,710)
      WRITE(6,350)
      WRITE(6,351)
      WRITE(6,352)
```

D-1 (CONT.)

```
      WRITE(6,353)
      WRITE(6,354) RADIUS
      WRITE(6,355)
      WRITE(6,356) PAO
      WRITE(6,357) TAC
      WRITE(6,358) RPMO
      WRITE(6,359) TORQO
      WRITE(6,610)
      WRITE(6,691)
C *****  VALUES OF VELOCITIES IN THREE DIRECTIONS
      DO 34 I=1,N1
      V1(I)=(((1-((PS1(I)/PT1(I))**GAM1))*2/GAM1*RG(I)
     1/RGO)**0.5)
      RHO1(I)=PT1(I)/PAC*RGC/RG(I)*((PS1(I)/PT1(I))
     1**GAMM)
      VR1(I)=V1(I)*DSIN(LAM(I))
      VU1(I)=V1(I)*DCOS(LAM(I))*DSIN(ALPH1(I))
      VA1(I)=V1(I)*DCOS(LAM(I))*DCOS(ALPH1(I))
      W1(I)=(((U   -VU1(I))**2)+VA1(I)*VA1(I)+VR1(I)
     1*VR1(I))**0.5
      VUV(I)=DSIN(ALPH1(I))*DCOS(LAM(I))
      ACTAL(I)=DARSIN(VUV(I))
      BETA(I)=(U-VU1(I))/W1(I)
      ACBTA(I)=DARSIN(BETA(I))
      VRV(I)=DSIN(LAM(I))/DCOS(ACTAL(I))
      ACTLAM(I)=DARSIN(VRV(I))
      ALPH1(I)=ALPH1(I)*180/PI
      LAM(I)=LAM(I)*180/PI
      ACTAL(I)=ACTAL(I)*180/PI
      ACBTA(I)=ACBTA(I)*180/PI
      ACTLAM(I)=ACTLAM(I)*180/PI
      WRITE(6,690) PER1(I),V1(I),VU1(I),VA1(I),VR1(I),W1(I),AC
     1TAL(I),ACBTA(I),ACTLAM(I)
   34 CONTINUE
      WRITE(6,710)
      WRITE(6,609)
      WRITE(6,692)
      DO43 I=1,N2
      WDOT=PI/4*DN*DN*PAC/((RGO/32.174*TAO)**0.5)*((PNREF
     1*2/PAO)**0.5)
      TT2TA=1+TORQC*PI*RPMO/30/(WDOT*RGC*GAMM1*TAC)
      V2(I)=((1-((PS2(I)/PT2(I))**GAM1))*2*GAMM1*TT2TA*RG
     12(I)/RGC)**0.5
      RHO2(I)=PT2(I)/PAO*RGO/RG2(I)*((PS2(I)/
     1PT2(I))**GAMM)/TT2TA
      VR2(I)=V2(I)*DSIN(LAM2(I))
      VU2(I)=V2(I)*DCOS(LAM2(I))*DSIN(ALPH2(I))
      VA2(I)=V2(I)*DCOS(LAM2(I))*DCOS(ALPH2(I))
```

D-1 (CONT.)

```
      W2(I)=(((U-VU2(I))**2)+VA2(I)*VA2(I)+VR2(I)*
     1VR2(I))**C.5
      VUV2(I)=DSIN(ALPH2(I))*DCOS(LAM2(I))
      ACTAL2(I)=DARSIN(VUV2(I))
      BETA2(I)=(U-VU2(I))/W2(I)
      ACBTA2(I)=DARSIN(BETA2(I))
      VRV2(I)=DSIN(LAM2(I))/DCOS(ACTAL2(I))
      ACLAM2(I)=DARSIN(VRV2(I))
      ALPH2(I)=ALPH2(I)*180/PI
      LAM2(I)=LAM2(I)*180/PI
      ACTAL2(I)=ACTAL2(I)*180/PI
      ACBTA2(I)=ACBTA2(I)*180/PI
      ACLAM2(I)=ACLAM2(I)*180/PI
      WRITE(6,690) PER2(I),V2(I),VU2(I),VA2(I),VR2(I),W2(I),AC
     1TAL2(I),ACBTA2(I),ACLAM2(I)
   43 CONTINUE
C *****  DETERMINATION OF AVG. TOTAL PRESSURES ANC AVG PERIPH-
C        ERAL VELOCITY USING TRAPEZOICAL INTEGRATION.
C *****  INITIAL CONDITIONS
      X1(1)=0
      Y1(1)=0
      VI(1)=0
      WI(1)=0
      P1(1)=0
      R1(1)=0
      S1(1)=0
      Q1(1)=0
C *****  AHEAD OF ROTOR
      DO13 I=2,N1
      X(I)=((VA1(I-1)*RHO1(I-1)*PT1(I-1)/PAO)+VA1(I)*RHO1(I)
     1*PT1(I)/PAO)*DTHETA(I)/2
      X1(I)=X1(I-1)+X(I)
      Y(I)=(VA1(I-1)*RHO1(I-1)+VA1(I)*RHO1(I))*DTHETA(I)/2
      Y1(I)=Y1(I-1)+Y(I)
      V(I)=(RHO1(I-1)*VA1(I-1)*VU1(I-1)+RHO1(I)*VA1(I)*VU1
     1(I))*DTHETA(I)/2
      VI(I)=VI(I-1)+V(I)
      W(I)=(RHO1(I-1)*VA1(I-1)+RHO1(I)*VA1(I))*DTHETA(I)/2
      WI(I)=WI(I-1)+W(I)
   13 CONTINUE
      PT1PAO=X1(N1)/Y1(N1)
      VU1BAR=VI(N1)/WI(N1)
C *****  AFTER ROTOR
      DO23 I=2,N2
      P(I)=((VA2(I-1)*RHO2(I-1)*PT2(I-1)/PAO)+VA2(I)*RHO2(I)
     1*PT2(I)/PAO)* THETA2(I)/2
      P1(I)=P1(I-1)+P(I)
      R(I)=(VA2(I-1)*RHO2(I-1)+VA2(I)*RHO2(I))*  THETA2(I)/2
```

D-1 (CONT.)

```
      R1(I)=R1(I-1)+R(I)
      S(I)=(RHO2(I-1)*VA2(I-1)*VU2(I-1)+RHO2(I)*VA2(I)*VU2(I
     1))* THETA2(I)/2
      S1(I)=S1(I-1)+S(I)
      Q(I)=(RHO2(I-1)*VA2(I-1)+RHO2(I)*VA2(I))* THETA2(I)/2
      Q1(I)=Q1(I-1)+Q(I)
   23 CONTINUE
      PT2PAO=P1(N2)/R1(N2)
      VU2BAR=S1(N2)/Q1(N2)
C ***** CALCULATION OF EFFICIENCY
      ETAR=(((PT2PAO/PT1PAO)**(GAM1))-1)/GAM1/U/(VU2BAR-
     1VU1BAR)
      PT21=PT2PAO/PT1PAO
      WRITE(6,360)PT21
      WRITE(6,361) VU1BAR,VU2BAR
      WRITE(6,363) ETAR
      WRITE(6,710)
  710 FORMAT('1')
  350 FORMAT(/,T45,'NON-DIMENSIONAL FLUID CONDITIONS ACROSS')
  351 FORMAT(T45,'ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL')
  352 FORMAT(T45,'SURVEY. ALL TEMPERATURES AND PRESSURES')
  353 FORMAT(T45,'REFERRED TO REFERENCE CONDITIONS')
  354 FORMAT(//,T55,'RADIUS=',F5.2)
  355 FORMAT(/,T13,'REFERENCE CONDITIONS')
  356 FORMAT(T15,'ATM.PRESS.(PSIA)=',F10.5)
  357 FORMAT(T15,'TEMP.(DEG.R)=',F10.5)
  358 FORMAT(T15,'COMPR.SPEED(RPM)=',F10.3)
  359 FORMAT(T15,'TORQUE(FT.LBF.)=',F10.5)
  610 FORMAT(/,T55,'BEFORE ROTOR',/)
  691 FORMAT(T14,'THETA',T27,'V1',T35,'VU1',T45,'VA1',T54,'VR1
     1',T66,'W1',T74,'ALPHA',T85,'BETA',T94,'LAMBDA')
  609 FORMAT(//,T55,'AFTER ROTOR',/)
  692 FORMAT(T14,'THETA',T27,'V2',T35,'VU2',T45,'VA2',T54,'VR2
     1',T66,'W2',T74,'ALPHA',T85,'BETA',T94,'LAMBDA')
  690 FORMAT(10X,F10.1,1X,8F10.5)
  360 FORMAT(/,T25,'PRESSURE RATIO ACROSS ROTOR=',F10.5)
  361 FORMAT(/,T25,'VU1BAR=',F10.5,8X,'VU2BAR=',F10.5)
  363 FORMAT(/,T25,'EFFICIENCY=',F10.5)
      STOP
      END
```

D-2. Fluid Conditions and Rotor Performance for Radius = 11.1

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=11.10

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
15.0	0.17786	0.05139	0.17021	0.00466	0.25279	16.79407	47.65562	1.56684
14.5	0.18474	0.05214	0.17716	0.00484	0.25698	16.39422	46.39713	1.56359
14.0	0.19052	0.05218	0.18317	0.00499	0.26113	15.89441	45.43648	1.55964
13.5	0.19442	0.05681	0.18581	-0.00679	0.25978	16.98933	44.29643	-2.09130
13.0	0.19700	0.06182	0.18692	-0.00688	0.25711	18.28846	43.32289	-2.10644
11.0	0.19891	0.07151	0.18532	-0.01041	0.24949	21.06970	41.93037	-3.21516
9.0	0.19891	0.07639	0.18352	-0.00694	0.24478	22.58547	41.38576	-2.16620
7.0	0.19891	0.07767	0.18299	-0.00694	0.24354	22.98519	41.24352	-2.17256
6.5	0.19762	0.07717	0.18180	-0.00690	0.24298	22.98519	41.51708	-2.17256
6.0	0.19575	0.07863	0.17913	-0.00683	0.24001	23.68468	41.67804	-2.18404
5.7	0.19189	0.07833	0.17511	-0.00502	0.23718	24.09122	42.38869	-1.64316
5.2	0.17929	0.07321	0.16366	0.0	0.23241	24.10000	45.23742	0.0
5.0	0.17360	0.06579	0.16040	0.00909	0.23568	22.26780	47.02618	3.24201
4.5	0.17145	0.05828	0.16099	0.00897	0.24162	19.87158	48.13932	3.19013
4.0	0.17577	0.05519	0.16688	0.0	0.24769	18.30000	47.64386	0.0
3.5	0.18275	0.05567	0.17401	0.0	0.25206	17.80000	46.34301	0.0
3.0	0.18933	0.05441	0.18135	0.0	0.25822	16.70000	45.38777	0.0
2.5	0.19191	0.05641	0.18337	-0.00502	0.25828	17.09396	44.74575	-1.56934
2.0	0.19585	0.05918	0.18657	-0.00684	0.25867	17.58893	43.80196	-2.09813
1.5	0.19842	0.06222	0.18813	-0.01038	0.25784	18.27403	43.05004	-3.15949
1.0	0.19972	0.06625	0.18812	-0.01045	0.25510	19.37235	42.38977	-3.18022
0.0	0.19972	0.07017	0.18669	-0.01045	0.25141	20.57049	41.94824	-3.20451

D-2 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
15.0	0.28100	0.19927	0.19788	-0.00981	0.20192	45.16486	11.12440	-2.83718
14.0	0.28147	0.20029	0.19751	-0.00982	0.20136	45.36462	10.86006	-2.84719
13.6	0.28189	0.19921	0.19921	-0.00984	0.20323	44.96511	11.06965	-2.82728
12.5	0.28189	0.19921	0.19921	-0.00984	0.20323	44.96511	11.06965	-2.82728
11.5	0.28145	0.19895	0.19895	-0.00737	0.20292	44.98037	11.16205	-2.12084
10.5	0.28098	0.19862	0.19862	-0.00736	0.20266	44.98037	11.27093	-2.12034
10.0	0.28009	0.19799	0.19799	-0.00733	0.20217	44.98037	11.48159	-2.12084
9.5	0.27826	0.19669	0.19669	-0.00728	0.20116	44.98037	11.91675	-2.12084
9.0	0.27829	0.19842	0.19499	-0.00728	0.19915	45.48002	11.52940	-2.13957
8.0	0.27786	0.19743	0.19538	-0.00727	0.19972	45.28016	11.78554	-2.13202
7.5	0.27786	0.19709	0.19572	-0.00727	0.20013	45.18023	11.86107	-2.12827
6.5	0.28094	0.19719	0.19997	-0.00735	0.20427	44.58064	11.58866	-2.10620
5.5	0.28183	0.19782	0.20060	-0.00738	0.20476	44.58064	11.38218	-2.10620
5.0	0.28276	0.19807	0.20156	-0.00987	0.20576	44.46571	11.25408	-2.80297
4.0	0.28365	0.20045	0.20045	-0.00990	0.20422	44.96511	10.66143	-2.82728
3.0	0.28458	0.20181	0.20040	-0.00993	0.20393	45.16486	10.28813	-2.83718
2.5	0.28551	0.20247	0.20106	-0.00996	0.20446	45.16486	10.07347	-2.83718
1.5	0.28551	0.20317	0.20035	-0.00996	0.20364	45.36462	9.91419	-2.84719
0.5	0.28547	0.20389	0.19967	-0.00747	0.20274	45.57995	9.75037	-2.14338
0.0	0.28458	0.20256	0.19975	-0.00745	0.20305	45.38009	10.11753	-2.13578

PRESSURE RATIO ACROSS ROTOR= 1.02931

VU1BAR= 0.06669 VU2BAR= 0.19954

EFFICIENCY= 0.91647

D-3. Fluid Conditions and Rotor Performance for Radius = 11.4

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=11.40

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
0.0	0.19699	0.06551	0.18499	-0.01717	0.25809	19.42281	43.96050	-5.30256
1.0	0.19702	0.06098	0.18656	-0.01717	0.26237	18.02875	44.43588	-5.25888
1.2	0.19446	0.05880	0.18424	-0.02033	0.26249	17.59986	45.07934	-6.29581
1.5	0.19055	0.05740	0.18094	-0.01661	0.26093	17.53085	45.86493	-5.24420
2.0	0.18068	0.05815	0.17081	-0.00946	0.25309	18.77327	47.47429	-3.16874
2.5	0.17363	0.06049	0.16264	-0.00606	0.24579	20.38702	48.53402	-2.13371
3.0	0.17365	0.06306	0.16174	0.00455	0.24323	21.29235	48.30140	1.60992
3.5	0.17938	0.06607	0.16603	0.01563	0.24435	21.61326	46.96082	5.37920
4.0	0.18354	0.07173	0.16818	0.01600	0.24175	23.00704	45.66968	5.43333
4.5	0.18936	0.07548	0.17360	0.00496	0.24245	23.49146	44.25084	1.63559
5.0	0.19518	0.07780	0.17893	0.00511	0.24472	23.49146	42.99043	1.63559
5.5	0.19770	0.07534	0.18279	0.0	0.24916	22.40000	42.81075	0.0
6.5	0.19768	0.07339	0.18348	-0.00517	0.25105	21.79215	43.01901	-1.61547
8.5	0.19767	0.07208	0.18393	-0.00690	0.25231	21.38632	43.15795	-2.14776
10.5	0.19767	0.06896	0.18444	-0.01723	0.25532	20.41850	43.48570	-5.33616
12.0	0.19767	0.06313	0.18652	-0.01723	0.26085	18.62622	44.10212	-5.27713
12.5	0.19509	0.06006	0.18484	-0.01700	0.26179	17.92917	44.84422	-5.25591
13.0	0.18676	0.05763	0.17738	-0.00977	0.25795	17.97449	46.47469	-3.15408
13.5	0.17645	0.06033	0.16575	-0.00462	0.24794	19.99285	48.02751	-1.59622
14.0	0.17362	0.06586	0.16058	0.00454	0.24037	22.29195	48.06261	1.62119
14.5	0.17651	0.07036	0.16181	0.00462	0.23788	23.49146	47.11722	1.63559
15.0	0.18074	0.07180	0.16512	0.01575	0.23958	23.40523	46.18417	5.44960

D-3 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
0.0	0.28109	0.19230	0.20478	-0.00981	0.21160	43.16723	14.32765	-2.74262
0.5	0.28196	0.19239	0.20559	-0.01476	0.21265	43.02656	14.23065	-4.10539
1.0	0.28286	0.19265	0.20659	-0.01480	0.21355	42.92682	14.09891	-4.09873
2.0	0.28286	0.19120	0.20793	-0.01480	0.21520	42.52784	14.38586	-4.07241
2.5	0.28192	0.18984	0.20790	-0.01475	0.21552	42.32834	14.73723	-4.05944
3.5	0.28102	0.18742	0.20888	-0.01471	0.21708	41.82959	15.29085	-4.02761
4.0	0.28106	0.18817	0.20825	-0.01471	0.21628	42.02909	15.14266	-4.04025
4.5	0.27920	0.18548	0.20818	-0.01461	0.21692	41.63008	15.83378	-4.01510
5.0	0.27829	0.18538	0.20733	-0.00971	0.21586	41.76880	15.94221	-2.68198
5.5	0.27739	0.18906	0.20275	-0.00968	0.21046	42.96746	15.31929	-2.73369
6.0	0.27650	0.18846	0.20210	-0.00965	0.20999	42.96746	15.52486	-2.73369
6.5	0.27512	0.18438	0.20406	-0.00720	0.21290	42.08226	16.44843	-2.02125
7.0	0.27351	0.18723	0.19938	0.0	0.20749	43.20000	16.06937	0.0
7.5	0.27258	0.18380	0.20129	0.0	0.21029	42.40000	16.82329	0.0
8.5	0.27365	0.19071	0.19611	0.00716	0.20353	44.18091	15.37289	2.09186
9.0	0.27361	0.19069	0.19609	0.00716	0.20351	44.18091	15.38132	2.09186
9.5	0.27522	0.19222	0.19697	0.0	0.20383	44.30000	14.91119	0.0
10.0	0.27756	0.19420	0.19831	0.0	0.20463	44.40000	14.27847	0.0
10.5	0.27891	0.19503	0.19916	-0.00973	0.20548	44.36583	13.97944	-2.79818
11.0	0.27979	0.19529	0.20012	-0.00976	0.20635	44.26595	13.84343	-2.79342
12.0	0.28161	0.19606	0.20161	-0.01474	0.20791	44.12369	13.52094	-4.18101
12.5	0.28251	0.19312	0.20566	-0.01479	0.21253	43.12631	14.03469	-4.11209
13.5	0.28254	0.19387	0.20501	-0.01479	0.21173	43.32579	13.88258	-4.12560
14.5	0.28117	0.18933	0.20735	-0.01472	0.21511	42.32834	14.90560	-4.05944
15.0	0.28026	0.18872	0.20668	-0.01467	0.21462	42.32834	15.10924	-4.05944

PRESSURE RATIO ACROSS ROTOR= 1.03063

VU1BAR= 0.06759 VU2BAR= 0.19048

EFFICIENCY= 1.00768

D-4. Fluid Conditions and Rotor Performance for Radius = 11.7

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=11.70

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
15.0	0.18965	0.07944	0.17193	0.00993	0.24316	24.76372	44.90840	3.30413
14.5	0.18770	0.08217	0.16848	0.00982	0.23879	25.96171	45.02892	3.33708
14.0	0.18773	0.07923	0.16991	0.00982	0.24188	24.96339	45.28225	3.30948
13.5	0.18642	0.07631	0.16980	0.00976	0.24389	24.16472	45.78246	3.28843
13.0	0.18462	0.07440	0.16869	0.00966	0.24449	23.76537	46.28232	3.27825
12.5	0.18192	0.06870	0.16833	-0.00635	0.24829	22.18576	47.27786	-2.15998
12.0	0.18767	0.06628	0.17448	-0.01962	0.25493	20.68082	46.47054	-6.41493
11.5	0.19484	0.06867	0.18079	-0.02375	0.2579[illegible]	20.63786	45.01398	-7.48267
11.0	0.19613	0.07481	0.17972	-0.02390	0.25288	22.42234	44.19752	-7.57573
9.0	0.19612	0.07665	0.17971	-0.01709	0.25104	23.00704	44.02104	-5.43333
7.0	0.19481	0.07763	0.17854	-0.00680	0.24903	23.48482	44.15443	-2.18071
5.0	0.19609	0.08070	0.17872	0.0	0.24694	24.30000	43.63642	0.0
4.0	0.19740	0.08049	0.17994	0.01033	0.24818	24.06488	43.42813	3.28587
3.5	0.19742	0.08519	0.17780	0.01033	0.24341	25.56238	42.97237	3.32536
3.0	0.19491	0.08287	0.17612	0.01020	0.24377	25.16306	43.64036	3.31488
2.5	0.19107	0.07951	0.17367	0.00500	0.24419	24.59101	44.64383	1.64956
2.0	0.18713	0.07549	0.17115	0.00490	0.24527	23.79134	45.72571	1.63934
1.5	0.18399	0.06799	0.17035	-0.00642	0.25052	21.68611	46.96513	-2.15241
1.0	0.18841	0.06358	0.17659	-0.01642	0.25811	19.72152	46.59711	-5.31242
0.5	0.19484	0.06976	0.18079	-0.02037	0.25687	20.97894	44.90801	-6.42770
0.0	0.19612	0.07148	0.18147	-0.02050	0.25616	21.37641	44.52458	-6.44507

D-4 (CONT.)

AFTER RCTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
15.0	0.27787	0.19518	0.19724	-0.01454	0.20553	44.62235	15.78799	-4.21683
14.5	0.27784	0.19516	0.19722	-0.01454	0.20551	44.62235	15.79631	-4.21683
13.5	0.27965	0.19596	0.19802	-0.02437	0.20699	44.48464	15.45167	-7.01695
13.0	0.28054	0.19414	0.20104	-0.02445	0.21038	43.78982	15.71004	-6.93446
12.5	0.28145	0.19524	0.20218	-0.01473	0.21027	43.92422	15.40575	-4.16694
11.5	0.28145	0.19630	0.20116	-0.01473	0.20901	44.22342	15.20114	-4.18810
10.5	0.28056	0.19742	0.19881	-0.01468	0.20645	44.72208	15.07178	-4.22411
10.0	0.27967	0.19901	0.19625	-0.00976	0.20328	45.36462	14.84903	-2.84719
9.5	0.27877	0.19871	0.19527	-0.00973	0.20241	45.46449	15.00114	-2.85224
9.0	0.27790	0.19849	0.19437	-0.00727	0.20150	45.57995	15.13696	-2.14338
8.5	0.27881	0.19913	0.19500	-0.00730	0.20194	45.57995	14.91420	-2.14338
8.0	0.27700	0.19885	0.19270	-0.00725	0.19979	45.87974	15.16057	-2.15492
7.5	0.27609	0.19820	0.19207	-0.00723	0.19936	45.87974	15.38856	-2.15492
7.0	0.27508	0.19444	0.19444	-0.00720	0.20266	44.98037	16.23630	-2.12084
6.0	0.27508	0.19239	0.19647	-0.00720	0.20518	44.38078	16.62704	-2.09899
5.0	0.27508	0.19033	0.19847	-0.00720	0.20769	43.78117	17.01558	-2.07782
4.5	0.27599	0.19160	0.19841	-0.00963	0.20736	43.96630	16.67639	-2.77928
3.5	0.27779	0.19236	0.19989	-0.01454	0.20885	43.82448	16.33656	-4.15996
3.0	0.27959	0.19066	0.20304	-0.02437	0.21324	42.99560	16.46551	-6.84374
2.5	0.27959	0.19066	0.20304	-0.02437	0.21324	42.99560	16.46551	-6.84374
2.0	0.28137	0.19542	0.20095	-0.02452	0.20996	43.98836	15.38022	-6.95772
1.5	0.28048	0.19234	0.20268	-0.02445	0.21244	43.29345	16.05906	-6.87732
1.0	0.28230	0.19358	0.20399	-0.02460	0.21337	43.29345	15.64037	-6.87732
0.0	0.28226	0.19792	0.20070	-0.01477	0.20815	44.52262	14.80389	-4.20959

PRESSURE RATIO ACRCSS RCTCR= 1.03062

VU1BAR= 0.07610 VU2BAR= 0.19478

EFFICIENCY= 1.01637

D-5. Fluid Conditions and Rotor Performance for Radius = 12.0

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=12.00

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
0.0	0.19454	0.07139	0.17940	-0.02371	0.25961	21.53015	45.80924	-7.52800
0.5	0.18795	0.07213	0.17244	-0.01965	0.25397	22.56877	46.89078	-6.49965
1.0	0.18477	0.07628	0.16817	-0.00645	0.24734	24.38417	47.12445	-2.19597
1.5	0.19461	0.08651	0.17350	0.01696	0.24422	26.39135	44.45386	5.58349
2.0	0.19847	0.08418	0.17890	0.01730	0.24971	25.09745	43.96627	5.52282
2.5	0.19844	0.08417	0.17887	0.01730	0.24971	25.09745	43.97171	5.52282
6.0	0.19714	0.07984	0.18018	-0.00516	0.25312	23.89130	44.59178	-1.64061
8.5	0.19714	0.07674	0.18078	-0.01718	0.25626	22.90748	44.87542	-5.42932
11.0	0.19714	0.07503	0.18114	-0.02061	0.25797	22.37005	45.03250	-6.49029
11.5	0.19586	0.07454	0.17996	-0.02047	0.25748	22.37005	45.29655	-6.49029
11.8	0.19328	0.07306	0.17815	-0.01685	0.25701	22.21061	45.87271	-5.40188
12.2	0.18933	0.07696	0.17286	-0.00661	0.25007	23.98446	46.23140	-2.18910
12.5	0.18796	0.07941	0.17030	0.00492	0.24649	24.99084	46.27675	1.65498
13.0	0.19201	0.08174	0.17293	0.01673	0.24717	25.19698	45.33762	5.52734
13.5	0.19200	0.08294	0.17235	0.01673	0.24590	25.59512	45.23775	5.54566
14.0	0.19200	0.08285	0.17291	0.01005	0.24601	25.56238	45.24614	3.32586
14.5	0.19067	0.08077	0.17243	0.00998	0.24714	25.06322	45.66385	3.31217
15.0	0.19067	0.08047	0.17257	0.00998	0.24746	24.96339	45.68930	3.30948

D-5 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
0.0	0.28063	0.19851	0.19782	-0.01469	0.20696	45.02126	16.57297	-4.24616
0.5	0.27973	0.19601	0.19808	-0.02438	0.20884	44.48464	17.13560	-7.01695
1.5	0.27884	0.19539	0.19745	-0.02430	0.20842	44.48464	17.35039	-7.01695
2.0	0.27792	0.19625	0.19625	-0.01455	0.20611	44.92153	17.30112	-4.23877
3.0	0.27704	0.19834	0.19288	-0.01450	0.20228	45.71931	17.01847	-4.29899
3.5	0.27706	0.19951	0.19199	-0.00967	0.20081	46.06374	16.79773	-2.88307
4.0	0.27616	0.19887	0.19137	-0.00964	0.20040	46.06374	17.02608	-2.88307
5.0	0.27706	0.20197	0.18966	0.0	0.19763	46.80000	16.33283	0.0
5.5	0.27706	0.19856	0.19309	0.00725	0.20203	45.77981	16.97620	2.15105
6.5	0.27750	0.19895	0.19347	0.0	0.20215	45.80000	16.85073	0.0
7.5	0.27750	0.19827	0.19416	0.0	0.20301	45.60000	16.97676	0.0
8.5	0.27746	0.19749	0.19476	-0.00726	0.20393	45.38009	17.12489	-2.13578
9.0	0.27836	0.19808	0.19533	-0.00971	0.20441	45.36462	16.91274	-2.84719
9.5	0.27925	0.19871	0.19595	-0.00975	0.20483	45.36462	16.69255	-2.84719
10.0	0.27925	0.19787	0.19650	-0.01461	0.20588	45.12098	16.84802	-4.25359
11.0	0.27925	0.19719	0.19719	-0.01461	0.20673	44.92153	16.97504	-4.23877
12.0	0.27925	0.19650	0.19787	-0.01461	0.20759	44.72208	17.10184	-4.22411
12.5	0.27878	0.19720	0.19652	-0.01459	0.20609	45.02126	17.02478	-4.24616
13.0	0.27836	0.19928	0.19379	-0.01457	0.20289	45.71931	16.68770	-4.29899
14.0	0.27746	0.19661	0.19524	-0.01452	0.20504	45.12098	17.28747	-4.25359
15.0	0.27657	0.19867	0.19186	-0.01447	0.20121	45.91875	17.01237	-4.31445

PRESSURE RATIO ACROSS ROTOR= 1.03081

VU1BAR= 0.07919 VU2BAR= 0.19793

EFFICIENCY= 0.99656

D-6. Fluid Conditions and Rotor Performance for Radius = 12.5

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=12.50

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
15.0	0.19012	0.08293	0.17079	0.00995	0.25223	25.86188	47.29209	3.33425
14.5	0.18944	0.08174	0.17061	0.00991	0.25298	25.56238	47.50499	3.32586
14.0	0.19077	0.08232	0.17181	0.00998	0.25337	25.56238	47.21662	3.32586
13.5	0.19210	0.08628	0.17081	0.01674	0.25015	26.68992	46.67891	5.59808
13.0	0.19341	0.08784	0.17092	0.02189	0.24950	27.01088	46.31926	7.29992
12.5	0.19341	0.08992	0.16983	0.02189	0.24725	27.70517	46.16663	7.34609
12.2	0.19077	0.08805	0.16842	0.01663	0.24723	27.48608	46.80103	5.63814
12.0	0.18761	0.08418	0.16738	0.00982	0.24900	26.66051	47.67359	3.35729
11.5	0.18626	0.08105	0.16692	-0.01623	0.25135	25.79418	48.14780	-5.55497
11.0	0.19207	0.07815	0.17389	-0.02341	0.25871	24.00821	47.29832	-7.66675
10.5	0.19470	0.08289	0.17457	-0.02373	0.25574	25.19738	46.45877	-7.74041
10.0	0.19470	0.08289	0.17457	-0.02373	0.25574	25.19738	46.45877	-7.74041
8.5	0.19470	0.08228	0.17564	-0.01697	0.25639	24.99791	46.50670	-5.51832
7.0	0.19470	0.08523	0.17476	-0.01019	0.25327	25.96171	46.27758	-3.33708
5.5	0.19470	0.08621	0.17444	-0.00679	0.25223	26.28275	46.20264	-2.23071
4.0	0.19470	0.08748	0.17394	0.0	0.25088	26.70000	46.10632	0.0
2.5	0.19470	0.08827	0.17324	0.01019	0.25004	26.96000	46.04691	3.36618
1.5	0.19602	0.08956	0.17353	0.01708	0.24968	27.18752	45.70532	5.62292
1.0	0.19341	0.08956	0.17059	0.01686	0.24764	27.58559	46.19256	5.64327
0.8	0.19077	0.08649	0.16975	0.00998	0.24892	26.96000	46.91184	3.36618
0.5	0.18628	0.08221	0.16708	-0.00488	0.25012	26.19034	48.06432	-1.67167
0.0	0.18764	0.08047	0.16871	-0.01635	0.25298	25.39605	47.93136	-5.53645

D-6 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
15.0	0.27343	0.19768	0.18891	0.0	0.20167	46.30000	20.49108	0.0
14.0	0.27339	0.19753	0.18877	-0.00954	0.20181	46.26349	20.51938	-2.89356
13.0	0.27429	0.19818	0.18939	-0.00957	0.20217	46.26349	20.28479	-2.89356
12.5	0.27429	0.20098	0.18611	-0.01436	0.19842	47.11527	19.82423	-4.41070
11.5	0.27523	0.19804	0.19058	-0.01440	0.20362	46.01846	20.17681	-4.32224
10.5	0.27523	0.20134	0.18709	-0.01440	0.19923	47.01557	19.63183	-4.40244
10.0	0.27612	0.20199	0.18770	-0.01445	0.19959	47.01557	19.39611	-4.40244
9.0	0.27612	0.20285	0.18719	-0.00723	0.19842	47.27873	19.25034	-2.21128
8.0	0.27524	0.20248	0.18619	-0.00961	0.19771	47.36206	19.43745	-2.95333
7.5	0.27434	0.20188	0.18563	-0.00718	0.19728	47.37865	19.66798	-2.21546
6.5	0.27434	0.20032	0.18745	0.0	0.19939	46.90000	19.92734	0.0
5.5	0.27434	0.20025	0.18739	0.00718	0.19948	46.87902	19.93870	2.19474
5.0	0.27434	0.20025	0.18739	0.00718	0.19948	46.87902	19.93870	2.19474
4.0	0.27448	0.19837	0.18957	0.00718	0.20217	46.27946	20.22833	2.17059
3.0	0.27357	0.19606	0.19066	-0.00716	0.20400	45.77981	20.73189	-2.15105
2.5	0.27357	0.19601	0.19061	-0.00955	0.20407	45.76412	20.74028	-2.86753
1.5	0.27354	0.19483	0.19146	-0.01432	0.20556	45.42015	20.93264	-4.27611
0.5	0.27538	0.19600	0.19194	-0.02400	0.20650	45.37780	20.48619	-7.12750
0.0	0.27535	0.19598	0.19192	-0.02400	0.20648	45.37780	20.49479	-7.12750

PRESSURE RATIO ACROSS ROTOR= 1.03128

VU1BAR= 0.08510 VU2BAR= 0.19907

EFFICIENCY= 1.01192

D-7. Fluid Conditions and Rotor Performance for Radius = 13.0

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=13.00

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
0.0	0.18343	0.08862	0.16053	-0.00480	0.24908	28.88916	49.84991	-1.71326
0.5	0.19056	0.09486	0.16497	0.00997	0.24743	29.85486	48.09062	3.45958
1.0	0.19445	0.09273	0.17007	0.01695	0.25281	28.48119	47.46324	5.69059
2.0	0.19311	0.09054	0.17027	0.01011	0.25420	27.95826	47.85316	3.39683
3.0	0.19311	0.09054	0.17027	0.01011	0.25420	27.95826	47.85316	3.39683
4.5	0.19179	0.08883	0.16991	-0.00502	0.25507	27.58974	48.20896	-1.69251
6.0	0.19179	0.08785	0.17020	-0.01004	0.25614	27.25948	48.27032	-3.37521
7.5	0.19463	0.08863	0.17245	-0.01696	0.25743	27.08801	47.69167	-5.61791
9.0	0.19466	0.08939	0.17172	-0.02035	0.25662	27.33673	47.63720	-6.75762
10.0	0.19466	0.08591	0.17306	-0.02372	0.26038	26.18819	47.86811	-7.80548
10.5	0.19201	0.08593	0.17011	-0.02340	0.25839	26.58447	48.35147	-7.83248
10.8	0.18936	0.08491	0.16809	-0.01979	0.25753	26.64156	48.91097	-6.71580
11.0	0.18620	0.08464	0.16470	-0.01946	0.25550	27.03881	49.52643	-6.73951
11.5	0.18348	0.08755	0.16125	0.0	0.25031	28.50000	49.89581	0.0
11.8	0.18757	0.09144	0.16295	0.01635	0.24900	29.17772	48.87417	5.72892
12.0	0.19072	0.09302	0.16509	0.02159	0.24962	29.19268	48.16531	7.45074
12.5	0.19468	0.09289	0.16967	0.02204	0.25281	28.49855	47.40861	7.40091
13.0	0.19335	0.08900	0.17025	0.02189	0.25605	27.40762	47.90518	7.32610
13.5	0.19204	0.08863	0.16954	0.01674	0.25547	27.48608	48.17519	5.63814
14.0	0.19072	0.08655	0.16913	0.01662	0.25675	26.98849	48.55428	5.61291
14.5	0.18755	0.08773	0.16569	0.00491	0.25311	27.88960	49.08753	1.69717
15.0	0.18755	0.08623	0.16645	0.00491	0.25470	27.38982	49.17202	1.68944

D-7 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
0.0	0.27258	0.20292	0.18143	-0.01427	0.19726	48.11225	22.68798	-4.49577
0.5	0.27099	0.20408	0.17803	-0.00946	0.19339	48.86001	22.79471	-3.04078
1.0	0.27010	0.20480	0.17553	-0.01414	0.19110	49.30847	22.85062	-4.60418
1.5	0.26824	0.19953	0.17903	-0.00936	0.19610	48.06111	23.90691	-2.99325
2.0	0.26828	0.19930	0.17945	-0.00702	0.19648	47.97820	23.93297	-2.24103
2.5	0.27016	0.20234	0.17902	0.0	0.19474	48.50000	23.18335	0.0
3.5	0.27269	0.20573	0.17884	0.00714	0.19340	48.97742	22.26303	2.28569
4.5	0.27269	0.20580	0.17890	0.0	0.19330	49.00000	22.25279	0.0
5.0	0.27269	0.20360	0.18140	0.0	0.19645	48.30000	22.57069	0.0
6.0	0.27107	0.20239	0.18032	0.0	0.19592	48.30000	23.01927	0.0
7.0	0.27107	0.20383	0.17844	-0.00946	0.19386	48.76015	22.81564	-3.03472
7.5	0.27269	0.20505	0.17951	-0.00952	0.19438	48.76015	22.36160	-3.03472
8.0	0.27457	0.20328	0.18432	-0.00958	0.19950	47.76152	22.30672	-2.97596
8.5	0.27548	0.20396	0.18494	-0.00961	0.19982	47.76152	22.06101	-2.97596
9.5	0.27548	0.20218	0.18657	-0.01442	0.20228	47.21497	22.32108	-4.41900
10.0	0.27457	0.20199	0.18444	-0.02393	0.20130	47.36177	22.49438	-7.39265
11.0	0.27457	0.20199	0.18444	-0.02393	0.20130	47.36177	22.49438	-7.39265
11.5	0.27271	0.20062	0.18319	-0.02377	0.20067	47.36177	22.99463	-7.39265
12.5	0.27274	0.20113	0.18366	-0.01427	0.20000	47.51408	22.91611	-4.44418
13.5	0.27115	0.20011	0.18273	-0.00946	0.19925	47.56179	23.32541	-2.96459
14.5	0.27118	0.20216	0.18075	0.0	0.19641	48.20000	23.03243	0.0
15.0	0.27118	0.20247	0.18040	0.0	0.19596	48.30000	22.98802	0.0

PRESSURE RATIO ACROSS ROTOR= 1.03137

VU1BAR= 0.08910 VU2BAR= 0.20266

EFFICIENCY= 0.97933

D-8. Fluid Conditions and Rotor Performance for Radius = 13.75

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=13.75

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
15.0	0.18603	0.09634	0.15907	-0.00487	0.25463	31.18811	51.31732	-1.75349
14.5	0.18472	0.09455	0.15861	-0.00484	0.25574	30.78830	51.64800	-1.74616
14.0	0.18334	0.09357	0.15759	0.00480	0.25588	30.68834	51.96193	1.74435
13.5	0.18472	0.09427	0.15877	0.00484	0.25606	30.68834	51.65756	1.74435
13.0	0.18603	0.09485	0.15974	0.00974	0.25635	30.65339	51.36973	3.48785
12.5	0.18850	0.09384	0.16319	0.00987	0.25930	29.85486	50.91322	3.45958
12.0	0.18984	0.09853	0.16142	0.01655	0.25489	31.26701	50.45981	5.85236
11.5	0.18919	0.09735	0.16138	0.01649	0.25577	30.96857	50.63785	5.83392
11.3	0.18788	0.09695	0.16009	0.01637	0.25526	31.06805	50.91810	5.84004
11.0	0.18408	0.09450	0.15790	0.00482	0.25534	30.88825	51.77898	1.74798
10.5	0.18271	0.08907	0.15873	-0.01592	0.26057	29.17772	52.24982	-5.72892
10.3	0.18541	0.08968	0.16112	-0.01938	0.26179	28.92545	51.69123	-6.85903
10.0	0.18354	0.09023	0.16345	-0.02624	0.26340	28.59264	51.06001	-9.12004
9.5	0.19121	0.09575	0.16386	-0.02330	0.25910	30.05075	50.29986	-8.09383
8.5	0.19120	0.09460	0.16451	-0.02330	0.26040	29.65472	50.35221	-8.06157
7.5	0.19120	0.09350	0.16594	-0.01666	0.26164	29.27722	50.40097	-5.73451
6.5	0.19120	0.09724	0.16377	-0.01666	0.25739	30.57063	50.23951	-5.80976
5.0	0.19120	0.09489	0.16569	-0.01001	0.26007	29.75504	50.33948	-3.45612
3.5	0.19120	0.09901	0.16349	-0.00500	0.25535	31.18811	50.16813	-1.75349
2.0	0.19120	0.09891	0.16332	0.01001	0.25547	31.15246	50.17215	3.50610
1.0	0.19120	0.09924	0.16257	0.01666	0.25509	31.26701	50.15928	5.85236
0.5	0.19254	0.09764	0.16510	0.01678	0.25793	30.47114	49.95669	5.80380
0.0	0.18358	0.09955	0.15931	0.01644	0.25277	31.86386	50.68245	5.89007

D-8 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
15.0	0.26361	0.20008	0.17149	0.00690	0.19618	49.37710	28.97071	2.30423
14.5	0.26361	0.20392	0.16691	0.00690	0.19031	50.67602	28.62733	2.36744
13.5	0.26266	0.19853	0.17197	0.0	0.19723	49.10000	29.31556	0.0
12.5	0.26266	0.19751	0.17291	-0.00917	0.19876	48.76015	29.40705	-3.03472
11.5	0.26312	0.19740	0.17342	-0.01377	0.19952	48.61070	29.31905	-4.54008
10.5	0.26405	0.19761	0.17361	-0.02301	0.20043	48.45243	29.10327	-7.55101
10.0	0.26499	0.19832	0.17423	-0.02310	0.20064	48.45243	28.84075	-7.55101
9.0	0.26644	0.19941	0.17518	-0.02322	0.20096	48.45243	28.43620	-7.55101
8.0	0.26738	0.20424	0.17199	-0.01399	0.19502	49.80684	27.76950	-4.65151
7.5	0.26738	0.20544	0.17056	-0.01399	0.19320	50.20551	27.65268	-4.69033
7.0	0.26551	0.20416	0.16949	-0.00927	0.19257	50.25798	28.18107	-3.12919
6.5	0.26457	0.20343	0.16889	-0.00923	0.19239	50.25798	28.45527	-3.12919
6.0	0.26362	0.20271	0.16829	-0.00920	0.19221	50.25798	28.73105	-3.12919
5.0	0.26362	0.20306	0.16798	-0.00690	0.19167	50.37627	28.70014	-2.35244
4.0	0.26362	0.20046	0.17121	0.0	0.19563	49.50000	28.93277	0.0
3.0	0.26457	0.20319	0.16929	0.00693	0.19276	50.17644	28.47725	2.34258
2.5	0.26408	0.20282	0.16898	0.00691	0.19266	50.17644	28.61940	2.34258
2.0	0.26362	0.20247	0.16869	0.00690	0.19257	50.17644	28.75245	2.34258
1.0	0.26361	0.20098	0.17044	-0.00690	0.19483	49.67685	28.88983	-2.31841
0.5	0.26359	0.19972	0.17178	-0.00920	0.19670	49.25944	29.00734	-3.06534
0.0	0.26457	0.20046	0.17242	-0.00923	0.19690	49.25944	28.72931	-3.06534

PRESSURE RATIO ACROSS ROTOR= 1.03132

VU1BAR= 0.09592 VU2BAR= 0.20093

EFFICIENCY= 0.99972

D-9. Fluid Conditions and Rotor Performance for Radius = 14.4

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=14.40

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
0.0	0.18973	0.10239	0.15887	0.01654	0.26120	32.65960	52.30016	5.94212
1.0	0.18973	0.10124	0.16015	0.00993	0.26255	32.25037	52.32719	3.54790
2.5	0.18971	0.10329	0.15905	0.00497	0.26012	32.98725	52.28249	1.78837
4.0	0.18837	0.09920	0.15999	-0.00657	0.26397	31.77836	52.65458	-2.35287
5.5	0.18838	0.09749	0.16035	-0.01642	0.26597	31.16753	52.69628	-5.84618
7.0	0.18970	0.09830	0.16103	-0.01983	0.26598	31.20861	52.40929	-7.01993
8.0	0.18970	0.10081	0.15947	-0.01983	0.26303	32.10179	52.34268	-7.08807
9.0	0.18970	0.09726	0.16123	-0.02312	0.26718	30.84272	52.43899	-8.16031
9.5	0.18908	0.09525	0.16170	-0.02304	0.26905	30.24876	52.62231	-8.11020
9.8	0.18387	0.09590	0.15527	-0.02241	0.26466	31.43661	53.64735	-8.21193
10.0	0.18115	0.09171	0.15507	-0.01894	0.26766	30.41455	54.29229	-6.96186
10.3	0.17840	0.09365	0.15105	-0.01555	0.26354	31.66492	54.81739	-5.87737
10.5	0.17840	0.09950	0.14808	0.0	0.25659	33.90000	54.75283	0.0
11.0	0.18659	0.10340	0.15446	0.01626	0.25771	33.65417	52.93865	6.01014
11.5	0.18654	0.10012	0.15655	0.01626	0.26158	32.46067	53.00851	5.92891
12.0	0.18522	0.09805	0.15631	0.01614	0.26303	31.96333	53.32419	5.89646
12.5	0.18390	0.09759	0.15557	0.00962	0.26270	32.05076	53.60574	3.54013
13.0	0.18256	0.09725	0.15443	0.00478	0.26217	32.18764	53.89033	1.77248
13.5	0.18187	0.10008	0.15178	0.00476	0.25832	33.38705	53.99494	1.79656
14.0	0.18324	0.10193	0.15227	0.0	0.25707	33.80000	53.67794	0.0
14.5	0.18594	0.09960	0.15694	-0.00487	0.26177	32.38754	53.14302	-1.77640
15.0	0.18660	0.09995	0.15750	-0.00488	0.26183	32.38754	52.99949	-1.77640

D-9 (CONT.)

AFTER-ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
0.0	0.25666	0.19911	0.16181	-0.00672	0.19574	50.87585	34.17073	-2.37758
0.5	0.25765	0.20441	0.15685	0.0	0.18855	52.50000	33.70978	0.0
1.0	0.25765	0.20441	0.15685	0.0	0.18855	52.50000	33.70978	0.0
1.5	0.25861	0.20537	0.15702	0.00677	0.18828	52.57433	33.41230	2.46868
2.0	0.25861	0.20204	0.16129	0.00677	0.19368	51.37541	33.54104	2.40345
2.5	0.25859	0.20377	0.15921	0.0	0.19087	52.00000	33.47542	0.0
3.0	0.25859	0.20146	0.16198	-0.00677	0.19457	51.17559	33.56970	-2.39301
3.5	0.25811	0.20221	0.16027	-0.00676	0.19274	51.57524	33.66415	-2.41401
4.5	0.25811	0.20410	0.15775	-0.00901	0.18968	52.25486	33.59286	-3.26828
5.5	0.25907	0.20078	0.16317	-0.01356	0.19629	50.80348	33.47751	-4.75024
6.5	0.25970	0.20191	0.16176	-0.02263	0.19534	51.02866	33.26367	-7.96554
7.5	0.26077	0.20274	0.16242	-0.02273	0.19545	51.02866	32.95321	-7.96554
8.0	0.26059	0.20175	0.16337	-0.02271	0.19678	50.73153	33.04550	-7.91458
9.0	0.25911	0.20060	0.16244	-0.02258	0.19662	50.73153	33.47595	-7.91458
9.5	0.25912	0.20258	0.15999	-0.02258	0.19350	51.42477	33.38315	-8.03484
10.5	0.25816	0.20294	0.15798	-0.02250	0.19164	51.82080	33.62357	-8.10575
11.5	0.25716	0.20422	0.15614	-0.00673	0.18819	52.57433	33.85173	-2.46868
12.5	0.25816	0.20618	0.15537	0.0	0.18634	53.00000	33.51058	0.0
13.5	0.25916	0.20588	0.15741	0.0	0.18821	52.60000	33.24357	0.0
14.5	0.26241	0.20536	0.16335	0.0	0.19348	51.50000	32.40589	0.0
15.0	0.25916	0.20275	0.16127	-0.00678	0.19328	51.47532	33.36763	-2.40871

PRESSURE RATIO ACROSS ROTOR= 1.03031

VU1BAR= 0.09944 VU2BAR= 0.20318

EFFICIENCY= 0.93527

D-10. Fluid Conditions and Rotor Performance for Radius = 15.0

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=15.00

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
15.0	0.13460	0.10182	0.15384	-0.00644	0.26862	33.47690	55.02541	-2.39798
14.0	0.18255	0.10571	0.14875	-0.00478	0.26249	35.38605	55.45889	-1.83999
13.5	0.18119	0.10102	0.15034	-0.00474	0.26725	33.88681	55.74899	-1.80702
13.0	0.17978	0.10027	0.14922	0.0	0.26721	33.90000	56.05060	0.0
12.5	0.17978	0.10312	0.14727	0.0	0.26375	35.00000	56.05715	0.0
12.0	0.18259	0.10511	0.14900	0.00956	0.26326	35.14463	55.44921	3.66965
11.5	0.18532	0.10402	0.15307	0.00970	0.26647	34.14665	54.85968	3.62569
10.5	0.18386	0.10895	0.14724	0.01602	0.25941	36.33884	55.18536	6.21140
10.3	0.18252	0.10959	0.14596	0.0	0.25767	36.90000	55.49580	0.0
10.0	0.17701	0.10489	0.14228	0.00926	0.25968	36.34213	56.69781	3.72535
9.8	0.17417	0.10160	0.14139	-0.00456	0.26183	35.68589	57.29719	-1.84688
9.5	0.17559	0.09552	0.14653	-0.01530	0.27012	32.95798	56.94652	-5.96217
9.0	0.18181	0.09642	0.15253	-0.02216	0.27314	32.03041	55.64781	-8.26510
8.5	0.18519	0.10255	0.15204	-0.02577	0.26815	33.62472	54.89586	-9.62147
7.5	0.18655	0.10434	0.15296	-0.02273	0.26694	34.00917	54.59903	-8.45409
6.5	0.18798	0.10182	0.15679	-0.01965	0.27096	32.79640	54.32531	-7.14321
5.0	0.18798	0.10417	0.15561	-0.01638	0.26814	33.65417	54.29961	-6.01014
3.5	0.18661	0.10537	0.15388	-0.00651	0.26575	34.37610	54.57899	-2.42345
2.0	0.18661	0.10593	0.15356	0.00489	0.26506	34.58646	54.57656	1.82210
0.0	0.18661	0.10502	0.15395	0.00977	0.26617	34.24645	54.58075	3.62999

D-10 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
15.0	0.25517	0.20431	0.15229	-0.01335	0.19288	53.19478	37.57407	-5.01164
14.0	0.25416	0.20345	0.15220	-0.00665	0.19299	53.17376	37.87362	-2.50305
13.5	0.25419	0.20505	0.15008	-0.00665	0.19033	53.77318	37.88291	-2.53868
12.5	0.25419	0.20771	0.14653	0.0	0.18578	54.80000	37.93609	0.0
11.5	0.25419	0.20873	0.14507	0.0	0.18401	55.20000	37.96440	0.0
10.5	0.25419	0.20539	0.14977	0.0	0.18977	53.90000	37.88801	0.0
10.0	0.25318	0.20681	0.14589	-0.00663	0.18596	54.77218	38.24646	-2.60102
9.0	0.25216	0.20190	0.15049	-0.01320	0.19295	53.19478	38.46819	-5.01164
8.0	0.25216	0.20062	0.15118	-0.02198	0.19507	52.71163	38.45269	-8.27141
7.5	0.25318	0.20090	0.15249	-0.02207	0.19593	52.51370	38.15025	-8.23385
6.5	0.25420	0.20117	0.15381	-0.02215	0.19680	52.31575	37.85111	-8.19672
5.5	0.25518	0.20195	0.15440	-0.02224	0.19680	52.31575	37.56611	-8.19672
5.0	0.25518	0.20195	0.15440	-0.02224	0.19680	52.31575	37.56611	-8.19672
4.0	0.25420	0.20589	0.14849	-0.01330	0.18892	54.09127	37.89508	-5.11960
3.0	0.25420	0.20605	0.14860	-0.00887	0.18866	54.15163	37.89794	-3.41639
2.5	0.25322	0.20530	0.14807	-0.00663	0.18860	54.17279	38.19739	-2.56316
1.5	0.25322	0.20659	0.14627	-0.00663	0.18640	54.67228	38.22841	-2.59461
0.5	0.25322	0.20666	0.14632	0.0	0.18627	54.70000	38.23033	0.0
0.0	0.25420	0.20772	0.14653	0.0	0.18578	54.80000	37.93468	0.0

PRESSURE RATIO ACROSS ROTOR= 1.03151

VU1BAR= 0.10386 VU2BAR= 0.20456

EFFICIENCY= 0.96127

D-11. Fluid Conditions and Rotor Performance for Radius = 15.5

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=15.50

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
0.0	0.18266	0.10901	0.14625	0.00956	0.26739	36.64149	56.76110	3.73980
1.0	0.18267	0.10526	0.14922	0.00478	0.27203	35.18615	56.71305	1.83545
2.0	0.18267	0.10737	0.14779	0.0	0.26943	36.00000	56.73525	0.0
3.0	0.18335	0.10457	0.15046	-0.00640	0.27332	34.77575	56.56422	-2.43513
4.0	0.18337	0.10398	0.15073	-0.00960	0.27405	34.54565	56.55606	-3.64301
5.0	0.18337	0.10346	0.15109	-0.00960	0.27469	34.34625	56.55373	-3.63431
6.5	0.18473	0.10423	0.15166	-0.01610	0.27466	34.35029	56.27042	-6.05978
7.5	0.18335	0.10360	0.14961	-0.02234	0.27451	34.40481	56.55922	-8.49416
8.5	0.17778	0.09918	0.14594	-0.02167	0.27619	33.91026	57.70947	-8.44419
8.8	0.17354	0.09899	0.14138	-0.01814	0.27371	34.78052	58.61728	-7.31159
9.0	0.17209	0.10132	0.13793	-0.01799	0.26994	36.06978	58.98254	-7.43023
9.5	0.17500	0.10767	0.13782	-0.00611	0.26391	37.97274	58.48506	-2.53741
10.0	0.18063	0.11103	0.14160	0.01574	0.26347	37.92924	57.26433	6.34389
11.0	0.18201	0.10925	0.14550	0.00476	0.26666	36.88526	56.91099	1.87550
12.0	0.17992	0.10316	0.14733	0.00471	0.27276	34.98625	57.28831	1.83096
12.5	0.17780	0.10573	0.14288	-0.00465	0.26821	36.48547	57.79123	-1.86577
13.5	0.17783	0.10270	0.14504	-0.00621	0.27195	35.27529	57.73582	-2.45007
14.0	0.17921	0.10502	0.14508	-0.00625	0.27001	35.87474	57.46645	-2.46848
15.0	0.18198	0.10319	0.14959	-0.00952	0.27408	34.54585	56.84704	-3.64301

D-11 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
0.0	0.24957	0.20216	0.14634	0.0	0.19607	54.10000	41.72384	0.0
1.0	0.25057	0.20290	0.14687	-0.00656	0.19609	54.07289	41.43173	-2.55699
1.5	0.25057	0.20290	0.14687	-0.00656	0.19609	54.07289	41.43173	-2.55699
2.5	0.25057	0.20239	0.14758	-0.00656	0.19696	53.87308	41.40779	-2.54475
3.5	0.25057	0.20269	0.14672	-0.01311	0.19645	53.99167	41.42187	-5.10731
4.5	0.25057	0.20422	0.14459	-0.01311	0.19385	54.58925	41.49875	-5.18216
5.0	0.25057	0.20695	0.14065	-0.01311	0.18909	55.68463	41.66648	-5.32677
6.0	0.24954	0.20609	0.13901	-0.02175	0.18925	55.67810	41.97276	-8.89214
7.0	0.24954	0.20732	0.13827	-0.01306	0.18708	56.18244	42.06526	-5.39586
7.5	0.24954	0.20756	0.13791	-0.01306	0.18665	56.28200	42.08447	-5.40994
8.5	0.24856	0.20768	0.13642	-0.00651	0.18513	56.67012	42.46318	-2.73068
9.5	0.24961	0.20564	0.14133	-0.00653	0.19014	55.47144	41.91712	-2.64700
10.0	0.24961	0.20390	0.14383	-0.00653	0.19316	54.77218	41.80639	-2.60102
10.5	0.24956	0.20609	0.14059	-0.00653	0.18928	55.67123	41.96511	-2.66051
11.5	0.24854	0.20500	0.14037	-0.00651	0.18985	55.57134	42.25529	-2.65373
12.5	0.24854	0.20227	0.14428	-0.00651	0.19458	54.47248	42.07750	-2.58192
13.5	0.24854	0.20206	0.14413	-0.01301	0.19493	54.39006	42.06559	-5.15691
14.5	0.24956	0.20213	0.14578	-0.01306	0.19611	54.09127	41.72544	-5.11960
15.0	0.24956	0.20188	0.14614	-0.01306	0.19655	53.99167	41.71273	-5.10731

PRESSURE RATIO ACROSS ROTOR= 1.03162

VU1BAR= 0.10491 VU2BAR= 0.20435

EFFICIENCY= 0.94545

D-12. Fluid Conditions and Rotor Performance for Radius = 16.0

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=16.00

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
15.0	0.18061	0.10456	0.14713	-0.00630	0.28058	35.37520	58.34191	-2.45310
14.0	0.17782	0.10398	0.14417	-0.00465	0.27951	35.78584	58.93116	-1.84920
13.0	0.17640	0.10265	0.14338	-0.00462	0.28024	35.58594	59.20912	-1.84457
12.0	0.17782	0.10373	0.14435	-0.00465	0.27982	35.68589	58.92599	-1.84688
11.0	0.18203	0.11002	0.14495	0.00477	0.27476	37.18510	58.14179	1.88292
10.0	0.17919	0.11127	0.14039	0.00469	0.27131	38.38444	58.82069	1.91374
9.5	0.17638	0.11215	0.13605	0.00462	0.26833	39.48382	59.51470	1.94365
9.0	0.16789	0.10605	0.13003	-0.00586	0.27069	39.17154	61.25949	-2.58013
8.5	0.16566	0.09909	0.13197	-0.01444	0.27805	36.73648	61.47974	-6.24355
8.0	0.17345	0.10156	0.13979	-0.01512	0.27973	35.84175	59.82594	-6.17209
7.5	0.17912	0.10689	0.14288	-0.01561	0.27675	36.63707	58.71074	-6.23546
7.0	0.18054	0.10830	0.14320	-0.01887	0.27592	36.86299	58.43264	-7.50708
6.0	0.17910	0.10563	0.14379	-0.01561	0.27830	36.14001	58.68697	-6.19556
4.5	0.18192	0.10472	0.14845	-0.00952	0.28123	35.14463	58.06686	-3.66965
3.0	0.18196	0.10740	0.14674	-0.00635	0.27797	36.17446	58.10236	-2.47790
1.5	0.18196	0.10349	0.14608	0.0	0.27662	36.60000	58.12427	0.0
0.0	0.18196	0.11048	0.14450	0.00476	0.27414	37.38499	58.17073	1.88793

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
15.0	0.24394	0.20267	0.13516	-0.01277	0.19554	56.18244	46.02818	-5.39586
14.0	0.24394	0.20091	0.13808	-0.00851	0.19859	55.44925	45.84334	-3.52800
13.0	0.24292	0.20007	0.13751	-0.00848	0.19880	55.44925	46.13121	-3.52800
12.5	0.24292	0.20007	0.13751	-0.00848	0.19880	55.44925	46.13121	-3.52800
11.5	0.24190	0.19923	0.13693	-0.00844	0.19900	55.44925	46.41972	-3.52800
10.5	0.24190	0.19851	0.13797	-0.00844	0.20024	55.14981	46.34625	-3.50144
10.0	0.24190	0.20089	0.13448	-0.00844	0.19612	56.14790	46.60209	-3.59196
9.0	0.24088	0.20190	0.13111	-0.00841	0.19308	56.94629	47.12167	-3.66863
8.0	0.24088	0.20235	0.13041	-0.00841	0.19227	57.14588	47.18287	-3.63842
7.5	0.24190	0.20343	0.13060	-0.00844	0.19161	57.24567	46.92087	-3.69842
6.5	0.24286	0.20386	0.13138	-0.01271	0.19207	57.07836	46.58935	-5.52591
6.0	0.24283	0.20361	0.13172	-0.01271	0.19249	56.97882	46.56852	-5.51108
5.5	0.24388	0.20402	0.13300	-0.01276	0.19307	56.77974	46.20938	-5.48172
5.0	0.24388	0.20285	0.13477	-0.01276	0.19514	56.28200	46.07220	-5.40994
4.0	0.24388	0.20448	0.13229	-0.01276	0.19224	56.97882	46.26657	-5.51108
3.0	0.24388	0.20062	0.13840	-0.00851	0.19902	55.34944	45.83680	-3.51910
2.5	0.24388	0.20014	0.13910	-0.00851	0.19986	55.14981	45.78996	-3.50144
1.5	0.24337	0.19904	0.13989	-0.00637	0.20111	54.87207	45.86834	-2.60747
0.5	0.24337	0.20002	0.13850	-0.00637	0.19945	55.27166	45.96088	-2.63366
0.0	0.24337	0.20002	0.13850	-0.00637	0.19945	55.27166	45.96088	-2.63366

PRESSURE RATIO ACROSS ROTOR= 1.03192

VU1BAR= 0.10641 VU2BAR= 0.20132

EFFICIENCY= 0.96855

D-13. Fluid Conditions and Rotor Performance for Radius = 17.0

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=17.00

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
15.0	0.16708	0.10283	0.13161	0.00437	0.29326	37.98466	63.31735	1.90326
14.5	0.16554	0.10188	0.13040	-0.00433	0.29356	37.98466	63.61164	-1.90326
14.0	0.16404	0.10005	0.12992	-0.00429	0.29499	37.58488	63.85351	-1.89299
13.0	0.16251	0.09822	0.12940	-0.00425	0.29640	37.18510	64.10013	-1.88292
12.5	0.16334	0.09850	0.13024	-0.00428	0.29652	37.08515	63.93122	-1.88043
11.5	0.15949	0.09879	0.12509	-0.00557	0.29406	38.27244	64.79845	-2.54785
11.0	0.15308	0.09454	0.12014	-0.00801	0.29592	38.13824	65.99122	-3.81533
10.8	0.14979	0.09228	0.11726	-0.01305	0.29702	38.02863	66.59408	-6.35252
10.3	0.14417	0.08728	0.11375	-0.01507	0.30035	37.25954	67.54068	-7.54666
9.7	0.14028	0.08377	0.11157	-0.01466	0.30277	36.66470	68.18236	-7.48759
9.0	0.14413	0.08486	0.11552	-0.01507	0.30326	36.06978	67.40866	-7.43023
8.5	0.14996	0.08970	0.11947	-0.01307	0.30026	36.73648	66.40600	-6.24355
8.0	0.15721	0.09521	0.12498	-0.00549	0.29725	37.27342	65.11079	-2.51363
7.0	0.16714	0.10424	0.13058	-0.00438	0.29153	38.58433	63.37502	-1.91906
6.5	0.16788	0.10559	0.13039	-0.00586	0.29027	38.97174	63.27771	-2.57283
5.5	0.16788	0.10468	0.13113	-0.00586	0.29141	38.57214	63.22965	-2.55845
4.5	0.16714	0.10263	0.13184	-0.00438	0.29353	37.88472	63.29486	-1.90068
3.5	0.16854	0.10349	0.13294	-0.00441	0.29326	37.88472	63.02645	-1.90068
2.5	0.16852	0.10161	0.13436	-0.00441	0.29558	37.08515	62.94736	-1.88043
1.0	0.16854	0.10116	0.13473	0.00441	0.29615	36.88526	62.92367	1.87550
0.5	0.16552	0.10004	0.13130	0.00433	0.29583	37.18510	63.52869	1.88292
0.0	0.16176	0.09799	0.12863	0.00423	0.29628	37.28504	64.25268	1.88542

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
0.0	0.22072	0.18503	0.11879	-0.01924	0.21637	56.96194	56.21074	-9.19885
0.5	0.22183	0.18635	0.12010	-0.00774	0.21528	57.14588	56.01222	-3.68842
1.0	0.22405	0.18869	0.12067	-0.00586	0.21361	57.36931	55.55809	-2.78256
1.5	0.22511	0.18958	0.12124	-0.00589	0.21320	57.36931	55.29622	-2.78256
2.0	0.22732	0.19123	0.12276	-0.00595	0.21273	57.26943	54.70585	-2.77500
2.5	0.23039	0.19293	0.12577	-0.00603	0.21310	56.86989	53.78090	-2.74526
3.0	0.22729	0.19012	0.12441	-0.00595	0.21458	56.77001	54.51698	-2.73795
4.0	0.22729	0.19007	0.12438	-0.00793	0.21467	56.74670	54.50803	-3.64909
5.0	0.22620	0.18880	0.12402	-0.01184	0.21567	56.58065	54.71457	-5.45273
6.0	0.22620	0.18813	0.12405	-0.01971	0.21681	56.27078	54.59798	-9.03057
7.0	0.22398	0.18542	0.12413	-0.01952	0.21906	55.87568	54.99820	-8.93770
7.5	0.22290	0.18452	0.12353	-0.01943	0.21944	55.87568	55.26111	-8.93770
8.0	0.22203	0.18359	0.12337	-0.01935	0.22011	55.77689	55.43641	-8.91485
8.5	0.21979	0.18194	0.12180	-0.01916	0.22059	55.87568	56.01608	-8.93770
9.0	0.21788	0.18057	0.12043	-0.01899	0.22096	55.97447	56.51196	-8.96070
9.5	0.21676	0.17976	0.11898	-0.02266	0.22120	56.02871	56.80045	-10.78163
10.0	0.21563	0.17903	0.11805	-0.02254	0.22130	56.12694	57.10648	-10.80948
10.5	0.21553	0.17985	0.11680	-0.02254	0.21994	56.51977	57.25962	-10.92265
11.0	0.21733	0.18199	0.11728	-0.01894	0.21807	56.86322	56.98959	-9.17434
11.5	0.21981	0.18534	0.11762	-0.01150	0.21492	57.47648	56.64092	-5.58618
12.0	0.22149	0.18695	0.11864	-0.00580	0.21391	57.56908	56.26938	-2.79783
12.5	0.22257	0.18786	0.11922	-0.00583	0.21348	57.56908	56.00522	-2.79783
13.0	0.22476	0.18971	0.12039	-0.00588	0.21261	57.56908	55.46433	-2.79783
13.5	0.22473	0.18989	0.12005	-0.00588	0.21227	57.66896	55.51273	-2.80553
14.5	0.22473	0.18921	0.12101	-0.00784	0.21343	57.34546	55.37953	-3.70847
15.0	0.22361	0.18700	0.12237	-0.00780	0.21603	56.74670	55.41702	-3.64909

PRESSURE RATIO ACROSS ROTOR= 1.03174

VU1BAR= 0.09891 , VU2BAR= 0.18677

EFFICIENCY= 0.97904

D-14. Fluid Conditions and Rotor Performance for Radius = 17.5

NON-DIMENSIONAL FLUID CONDITIONS ACROSS
ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL
SURVEY. ALL TEMPERATURES AND PRESSURES
REFERRED TO REFERENCE CONDITIONS

RADIUS=17.50

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
15.0	0.15586	0.09699	0.12194	0.00408	0.30414	38.48438	66.34962	1.91639
14.5	0.15265	0.10075	0.11468	0.0	0.29780	41.30000	67.34995	0.0
13.5	0.14940	0.10093	0.11015	0.0	0.29592	42.50000	68.14746	0.0
10.5	0.14271	0.09822	0.10278	-0.01244	0.29606	43.49201	69.53033	-6.90000
9.5	0.13067	0.09020	0.09178	-0.02269	0.30064	43.65076	71.67024	-13.88602
8.5	0.12535	0.08435	0.09013	-0.02177	0.30564	42.29077	72.33924	-13.57643
8.0	0.12733	0.08291	0.09538	-0.01552	0.30821	40.62979	71.72788	-9.24056
7.7	0.13121	0.08454	0.09969	-0.01144	0.30785	40.11535	70.97740	-6.54402
7.6	0.13348	0.08494	0.10231	-0.01163	0.30835	39.51923	70.49278	-6.48726
7.5	0.13721	0.08648	0.10641	-0.00479	0.30810	39.07164	69.77357	-2.57647
7.3	0.14048	0.08761	0.10975	0.00368	0.30820	38.58433	69.12700	1.91906
7.1	0.14871	0.09335	0.11569	0.00389	0.30505	38.88416	67.69864	1.92713
7.0	0.14952	0.09568	0.11483	0.00391	0.30257	39.78364	67.68212	1.95209
6.9	0.15118	0.09478	0.11704	0.01318	0.30451	38.82366	67.24527	6.42314
6.7	0.15406	0.09741	0.11859	0.01343	0.30269	39.22114	66.77834	6.45950
6.5	0.15768	0.10118	0.12016	0.01374	0.29987	39.91665	66.21520	6.52491
5.5	0.16083	0.10516	0.12140	0.00842	0.29654	40.83202	65.77233	3.96631
4.5	0.16083	0.10431	0.12213	0.00842	0.29762	40.43297	65.71143	3.94264
3.0	0.15926	0.10340	0.12106	0.00417	0.29793	40.48323	66.00926	1.97230
1.5	0.15688	0.10433	0.11709	0.00411	0.29548	41.68251	66.63860	2.00864
0.0	0.14574	0.10032	0.10571	0.0	0.29487	43.50000	68.99113	0.0

D-14 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
15.0	0.21848	0.19408	0.10017	-0.00572	0.20739	62.66198	61.06645	-3.26767
14.0	0.21851	0.19434	0.09988	0.0	0.20694	62.80000	61.14127	0.0
13.5	0.21848	0.19425	0.09983	0.00572	0.20707	62.76182	61.12502	3.27874
13.0	C.21960	0.19542	0.10000	0.00575	0.20614	62.86166	60.92655	3.28989
12.5	0.22154	0.19715	0.10089	0.00580	0.20506	62.86166	60.47587	3.28989
12.0	0.22208	0.19781	0.10079	0.00581	0.20444	62.96149	60.40868	3.30113
11.5	0.22319	0.19879	0.10129	0.00584	0.20384	62.96149	60.14887	3.30113
11.0	0.22372	0.19969	0.10087	0.0	0.20276	63.20000	60.16590	0.0
10.0	0.22375	0.19965	0.10085	-0.00586	0.20287	63.16116	60.13581	-3.32387
9.5	0.22208	0.19811	0.10007	-0.00775	0.20389	63.13099	60.51045	-4.42876
9.0	0.22097	0.19606	0.10163	-0.00771	0.20644	62.53274	60.41559	-4.33939
8.5	0.22100	0.19593	0.10156	-0.01157	0.20669	62.44890	60.36051	-6.49688
8.0	0.21908	0.19353	0.10204	-0.01147	0.20901	62.05144	60.57710	-6.41142
7.5	0.21911	0.19320	0.10272	-0.01147	0.20964	61.85268	60.45913	-6.36964
6.5	0.21911	0.19211	0.10474	-0.01147	0.21158	61.25631	60.13173	-6.24793
5.5	0.21906	0.19262	0.10371	-0.01146	0.21063	61.55451	60.30450	-6.30811
5.0	0.21906	0.19276	0.10379	-0.00765	0.21037	61.63525	60.34892	-4.21273
4.0	0.21789	0.19250	0.10192	-0.00570	0.20962	62.06294	60.85815	-3.20300
3.0	0.21789	0.19327	0.10061	0.0	0.20823	62.50000	61.10816	0.0
2.5	0.21789	0.19327	0.10061	0.0	0.20823	62.50000	61.10816	0.0
2.0	0.21901	0.19461	0.10045	0.0	0.20698	62.70000	60.96731	0.0
1.5	0.22095	0.19680	0.10027	0.00578	0.20507	62.96149	60.67260	3.30113
1.0	0.22095	0.19652	0.10100	0.0	0.20559	62.80000	60.57667	0.0
0.5	0.22203	0.19836	0.09976	0.0	0.20338	63.30000	60.62370	0.0
0.0	0.22205	0.19855	0.09942	0.0	0.20305	63.40000	60.68159	0.0

PRESSURE RATIO ACROSS ROTOR= 1.03507

VU1BAR= 0.09908 VU2BAR= 0.19523

EFFICIENCY= 0.95929

D-15. Fluid Conditions and Rotor Performance for Radius = 17.75

NON-DIMENSIONAL FLUID CONDITIONS ACROSS ROTOR BLADE IN A 15 DEGREE CIRCUMFERENTIAL SURVEY. ALL TEMPERATURES AND PRESSURES REFERRED TO REFERENCE CONDITIONS

RADIUS=17.75

REFERENCE CONDITIONS***
ATM.PRESS.(PSIA)= 14.67040
TEMP.(DEG.R)= 515.00000
COMPR.SPEED(RPM)= 2315.000
TORQUE(FT.LBF.)= 158.74400

BEFORE ROTOR

THETA	V1	VU1	VA1	VR1	W1	ALPHA	BETA	LAMBDA
0.0	0.13999	0.10397	0.09362	-0.00489	0.29241	47.96125	71.30146	-2.98746
0.5	0.13998	0.10477	0.09269	-0.00489	0.29136	48.46056	71.42266	-3.01676
1.0	0.13996	0.10180	0.09593	-0.00488	0.29522	46.66297	71.01268	-2.91489
1.5	0.14380	0.10200	0.10129	0.00376	0.29679	45.18023	70.03089	2.12827
2.0	0.14553	0.10233	0.10341	0.00381	0.29721	44.68057	69.62453	2.10983
3.5	0.14890	0.10170	0.10868	0.00390	0.29968	43.08163	68.72206	2.05393
4.5	0.15053	0.10088	0.11165	0.00394	0.30153	42.08226	68.25279	2.02125
5.5	0.15218	0.09906	0.11476	0.01326	0.30464	40.61207	67.71511	6.59263
6.0	0.15218	0.09663	0.11681	0.01326	0.30766	39.41987	67.53551	6.47796
6.5	0.15057	0.09337	0.11739	0.01312	0.31089	38.32678	67.67049	6.37868
7.0	0.14557	0.08919	0.11498	0.00381	0.31362	37.78477	68.47942	1.89810
7.5	0.13825	0.08315	0.11034	-0.00482	0.31762	36.97370	69.65140	-2.50369
8.0	0.13280	0.08254	0.10339	-0.01157	0.31603	38.42616	70.77958	-6.38748
8.5	0.12512	0.08082	0.09429	-0.01525	0.31496	40.23495	72.34617	-9.18599
9.0	0.11432	0.08138	0.07941	-0.01598	0.31033	45.13149	74.86872	-11.37758
9.5	0.12161	0.09206	0.07807	-0.01482	0.29962	49.19899	74.61975	-10.74895
10.0	0.13333	0.10007	0.08699	-0.01394	0.29437	48.64023	72.58539	-9.10175
10.5	0.13517	0.09960	0.09063	-0.01178	0.29582	47.46094	72.00517	-7.40666
11.0	0.13515	0.09895	0.09195	-0.00472	0.29665	47.06245	71.91929	-2.93668
11.5	0.13699	0.10029	0.09320	-0.00478	0.29577	47.06245	71.60809	-2.93668
12.0	0.13698	0.09881	0.09475	-0.00478	0.29767	46.16362	71.41395	-2.88830
12.5	0.13879	0.09910	0.09704	-0.00484	0.29813	45.56437	70.97894	-2.85731
13.0	0.14055	0.10036	0.09828	-0.00491	0.29735	45.56437	70.67526	-2.85731
13.5	0.14441	0.10208	0.10208	-0.00378	0.29699	44.98037	69.88226	-2.12084
14.0	0.14785	0.10560	0.10341	-0.00387	0.29416	45.57995	69.40359	-2.14338
14.5	0.14781	0.10789	0.10096	-0.00387	0.29115	46.87902	69.69554	-2.19474
15.0	0.15116	0.10629	0.10741	-0.00396	0.29494	44.68057	68.62810	-2.10983

D-15 (CONT.)

AFTER ROTOR

THETA	V2	VU2	VA2	VR2	W2	ALPHA	BETA	LAMBDA
0.0	0.21577	0.19907	0.08246	0.01129	0.20002	67.31118	65.41099	7.79804
1.0	0.21577	0.19907	0.08246	0.01129	0.20002	67.31118	65.41099	7.79804
2.0	0.21462	0.19753	0.08182	0.01871	0.20171	66.97934	65.41130	12.87759
2.5	0.21462	0.19739	0.08216	0.01871	0.20198	66.88184	65.34152	12.82536
3.5	0.21347	0.19561	0.08343	0.01861	0.20410	66.39407	65.23985	12.57092
4.0	0.21117	0.19339	0.08409	0.01105	0.20584	66.32006	65.66754	7.48750
4.5	0.21000	0.19217	0.08396	0.01099	0.20690	66.22091	65.84167	7.45791
5.0	0.20882	0.19109	0.08349	0.01093	0.20769	66.22091	66.08328	7.45791
5.5	0.20762	0.18970	0.08367	0.01087	0.20903	66.02259	66.19418	7.39950
6.0	0.20386	0.19147	0.08325	0.00547	0.20703	66.45489	66.23443	3.75723
6.5	0.20883	0.19159	0.08291	0.00547	0.20678	66.55467	66.30818	3.77233
7.0	0.21119	0.19476	0.08147	0.00553	0.20331	67.25311	66.31898	3.88189
7.5	0.21235	0.19578	0.08149	0.01111	0.20262	67.21210	66.05050	7.76573
8.0	0.21235	0.19606	0.08081	0.01111	0.20208	67.41025	66.19346	7.83064
8.5	0.21464	0.19831	0.08133	0.01123	0.20024	67.50932	65.79337	7.86354
9.0	0.21578	0.19937	0.08177	0.01129	0.19946	67.50932	65.55383	7.86354
10.0	0.21578	0.19917	0.08087	0.01881	0.19985	67.36911	65.45060	13.09112
11.0	0.21578	0.19903	0.08122	0.01881	0.20012	67.27170	65.37927	13.03703
12.0	0.21578	0.19793	0.08239	0.02443	0.20219	66.53100	64.84745	16.51400
12.5	0.21461	0.19686	0.08194	0.02429	0.20297	66.53100	65.09589	16.51400
13.5	0.21461	0.19642	0.08297	0.02429	0.20377	66.24323	64.89513	16.32005
14.5	0.21225	0.19339	0.08409	0.02403	0.20695	65.66686	65.00152	15.94637
15.0	0.21225	0.19235	0.08645	0.02403	0.20885	64.99310	64.55838	15.53295

PRESSURE RATIO ACROSS ROTOR= 1.03394

VU1BAR= 0.09791 VU2BAR= 0.19611

EFFICIENCY= 0.89652

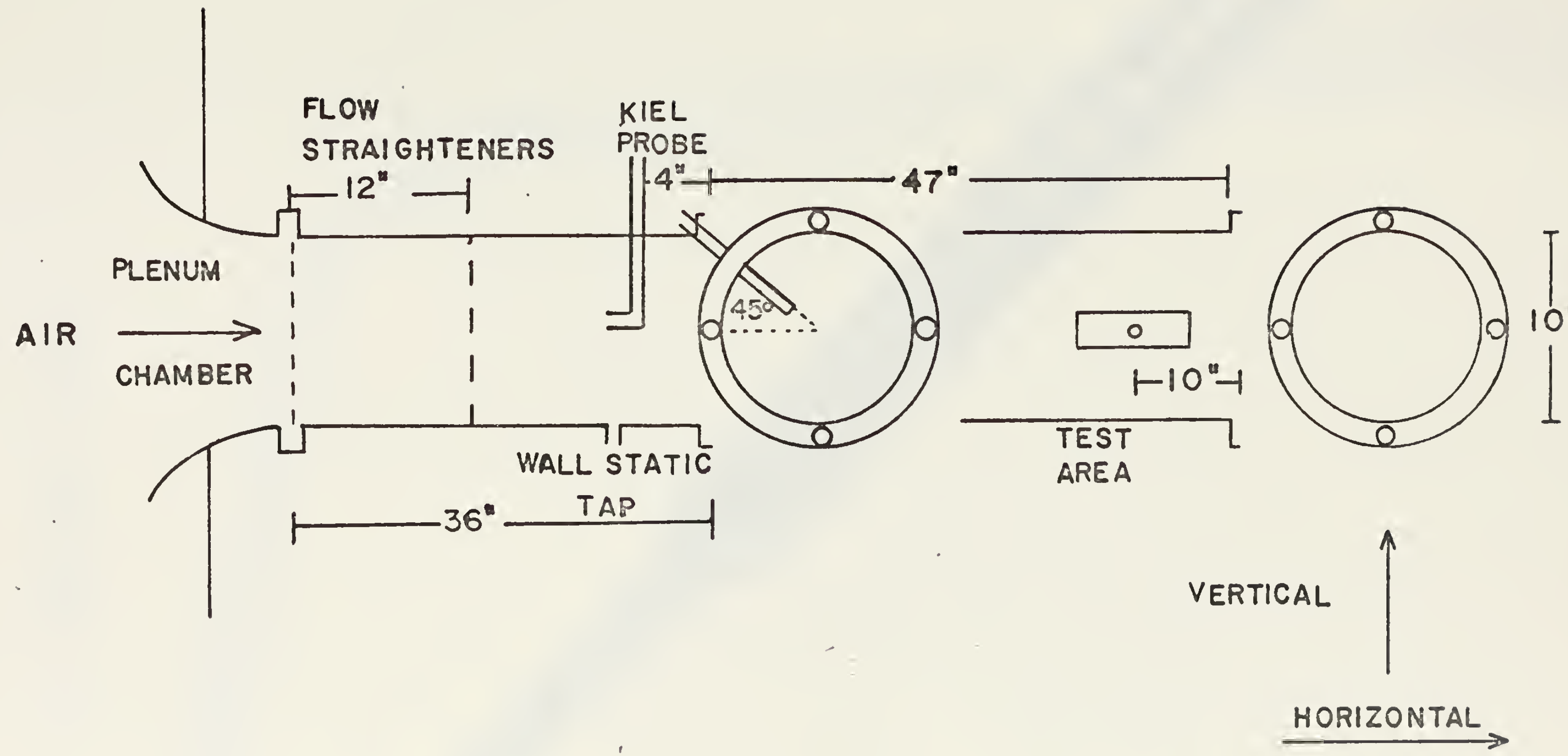


Figure 1. Schematic of the Test Apparatus for Probe Calibration

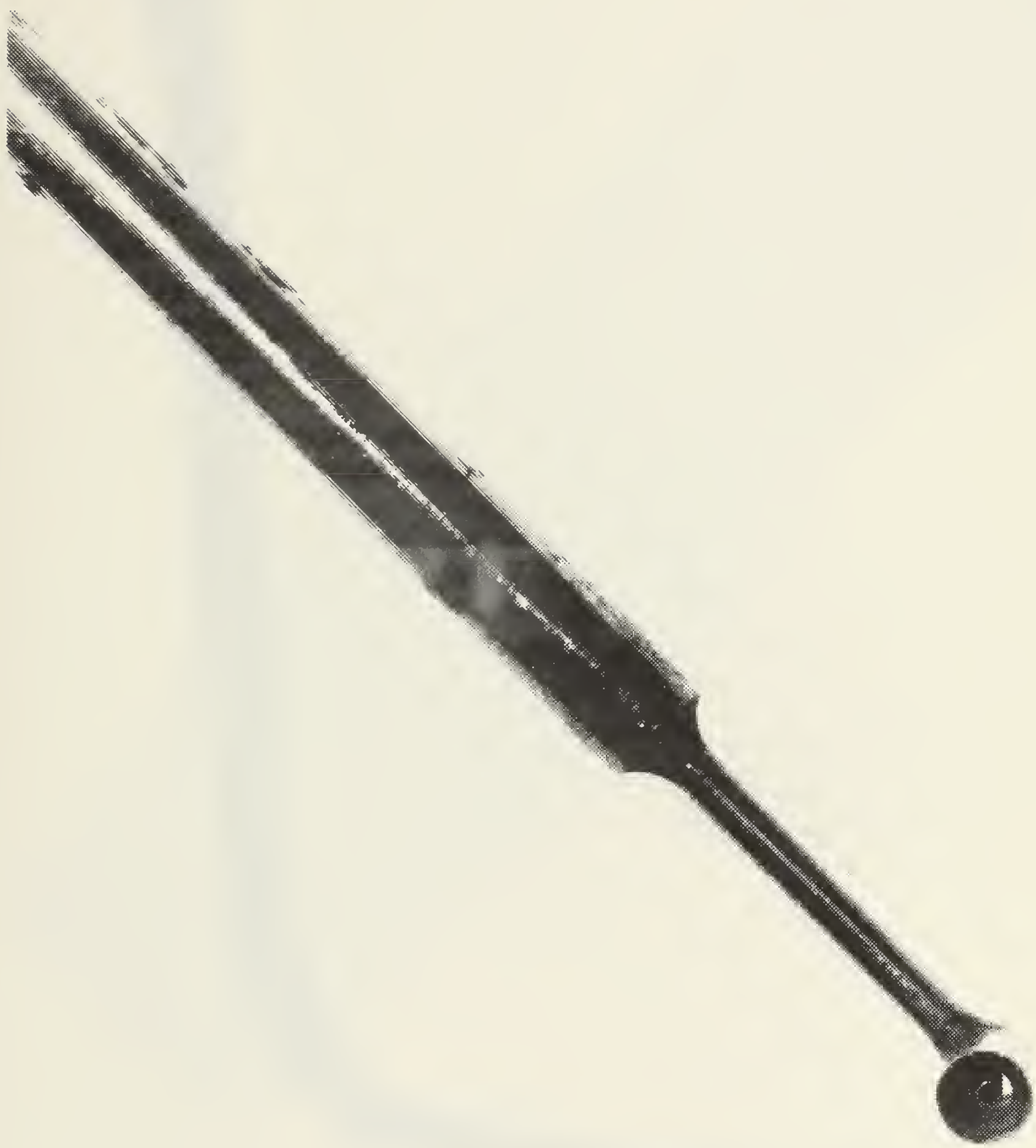


Figure 2. Kiel Probe

Figure 3: Prandtl Pitot-Static Probe

Figure 4. Enlargement of the Tip of a 1/8" Diameter

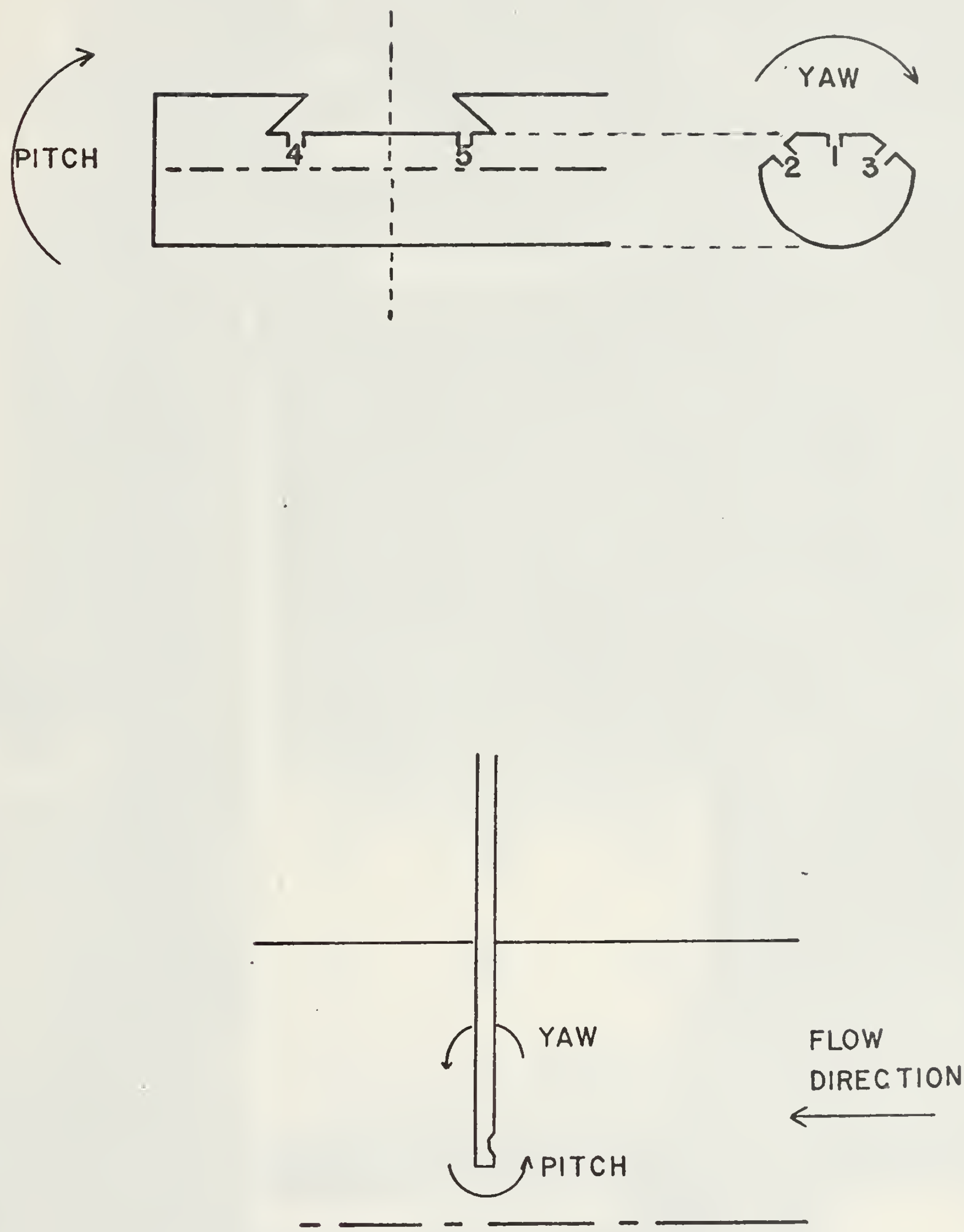


Figure 5: Location of Pressure Ports and Direction of Pitch and Yaw of 5-Hole Probe

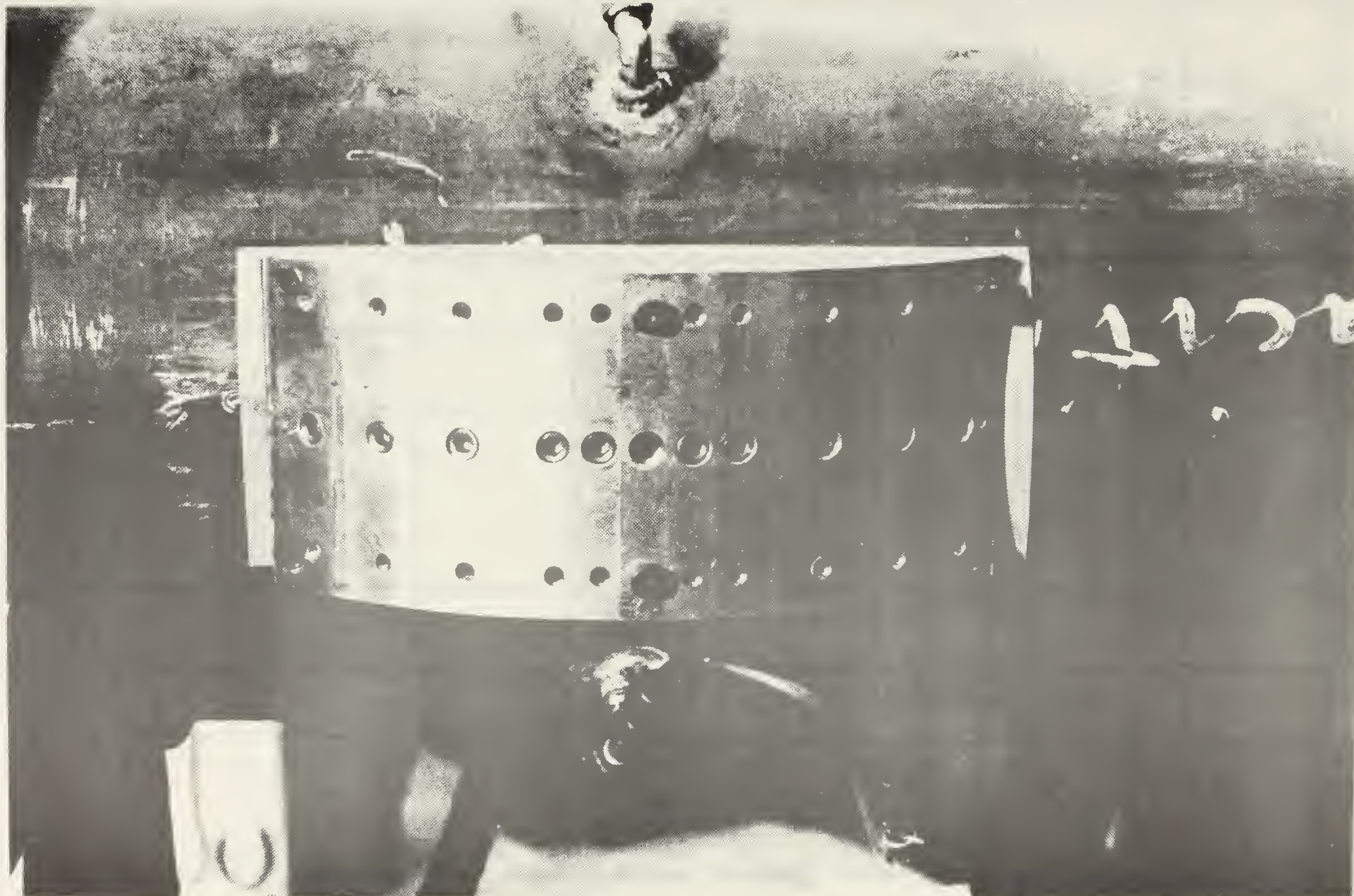


Figure 6. Mounting Block for Varying Pitch Angle

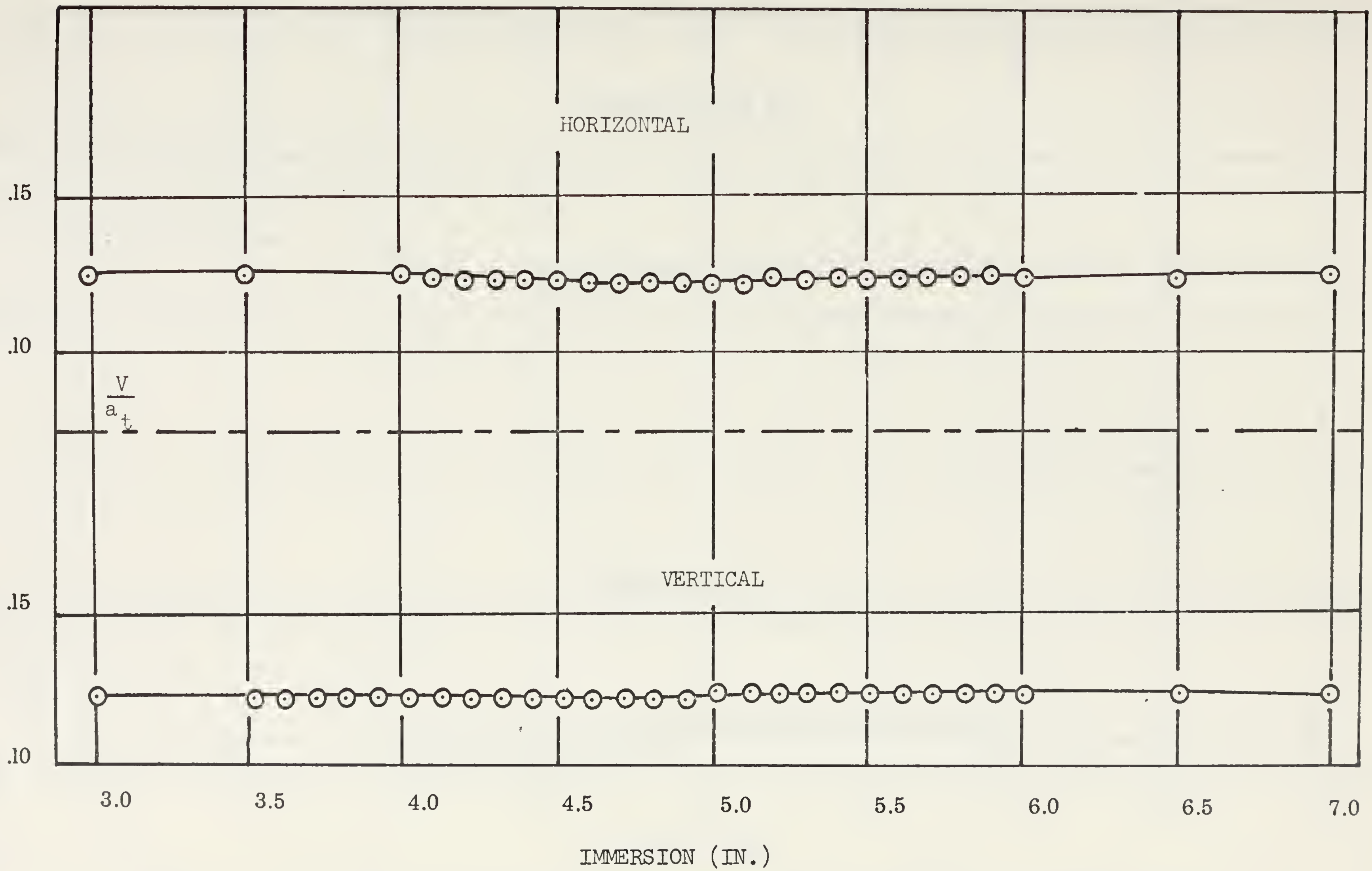


Figure 7: Non-Dimensional Velocity Versus Immersion Distance $P_{tk}-P_A = 5.0$ in. H_2O

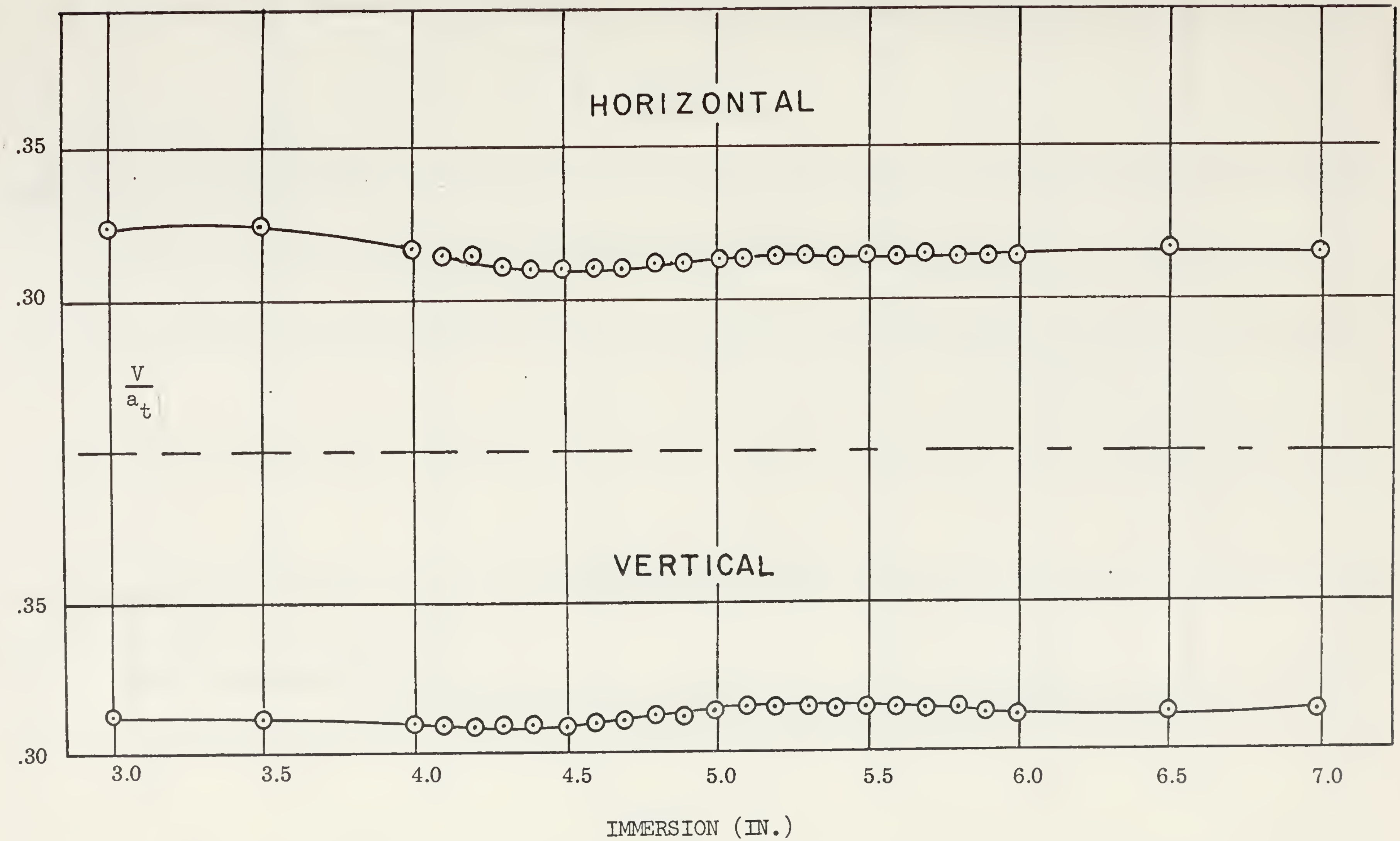


Figure 8. Non-Dimensional Velocity Versus Immersion Distance $P_{tk}-P_A = 35$ in. H_2O

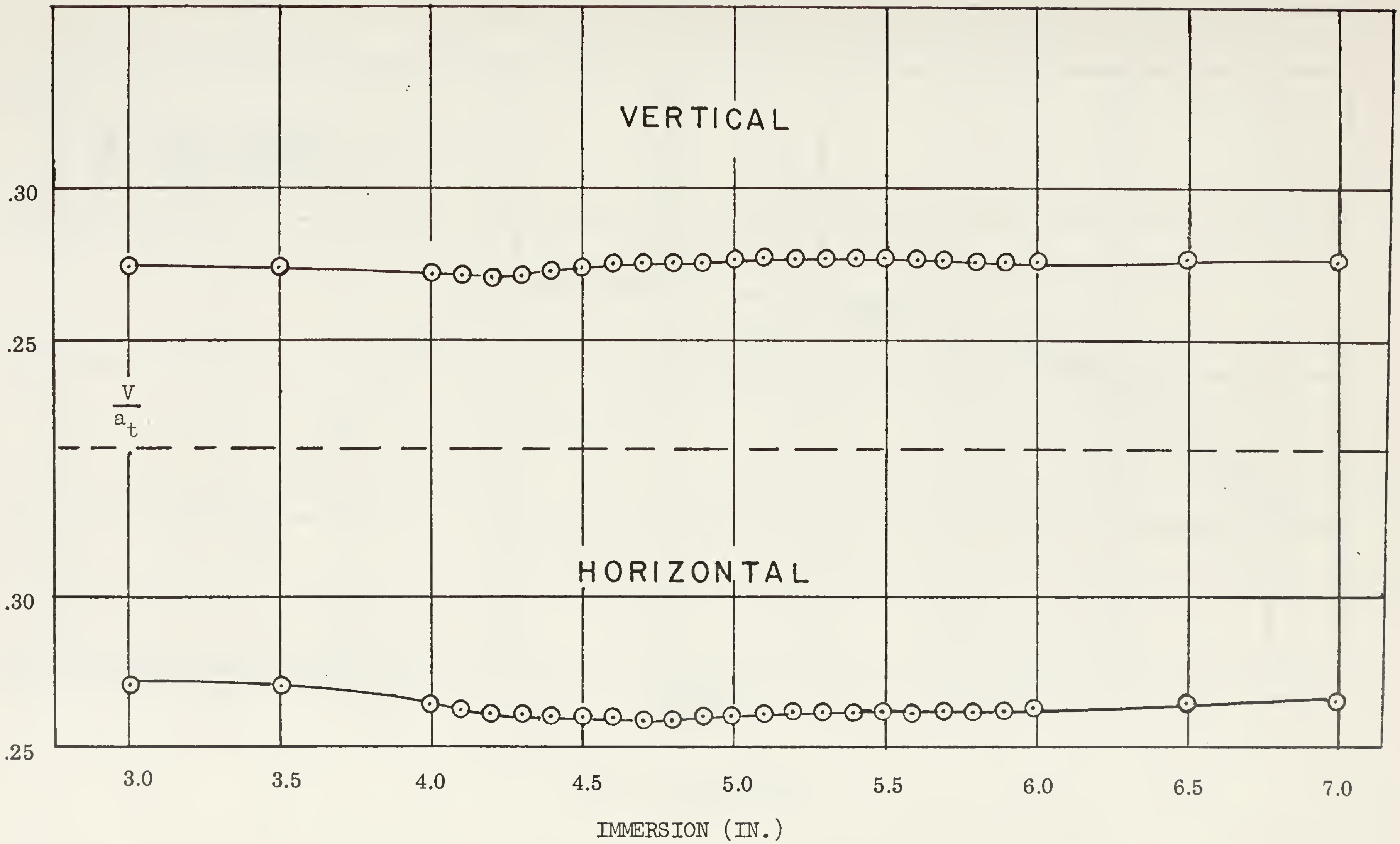
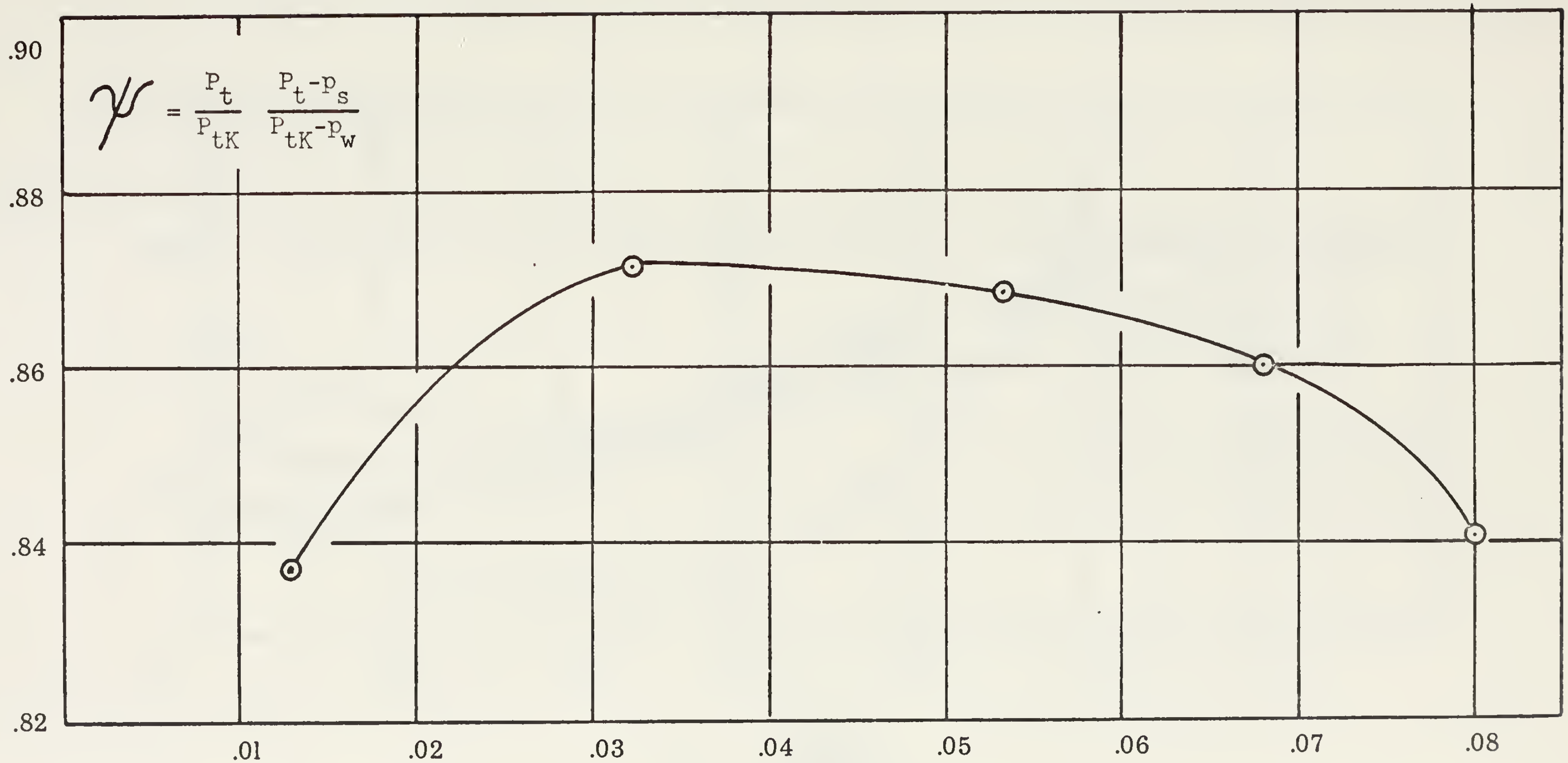
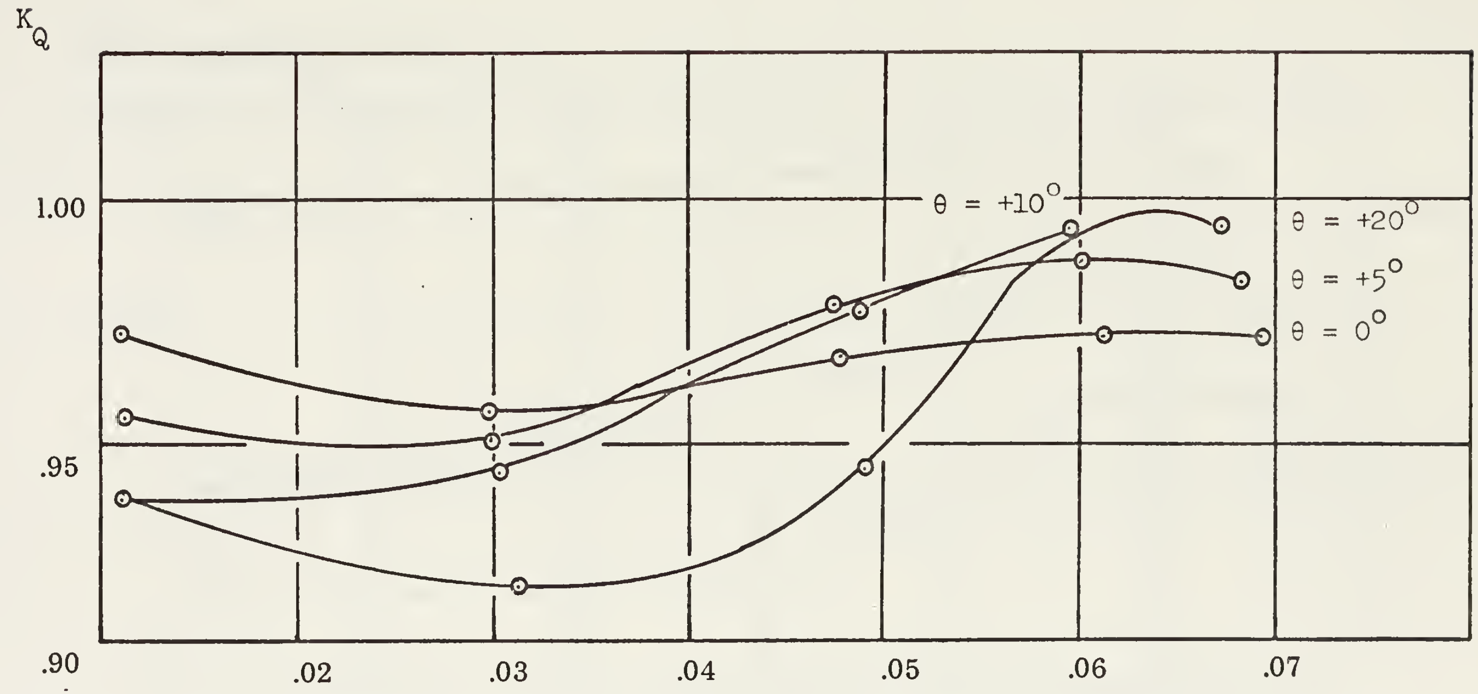


Figure 9. Non-Dimensional Velocity Versus Immersion Distance $P_{tk}-P_A = 23$ in. H_2O



$M_K = (P_{tK} - p_w)/P_{tK}$

Figure 10: Ψ Versus M_K



$$M_r = \frac{P_1 - P_{213}}{P_1}$$

Figure 11: K_Q Versus M_r for 5-Hole Probe DA 120 #538 for $\theta = 0^\circ$, $+5^\circ$, $+10^\circ$ and $+20^\circ$

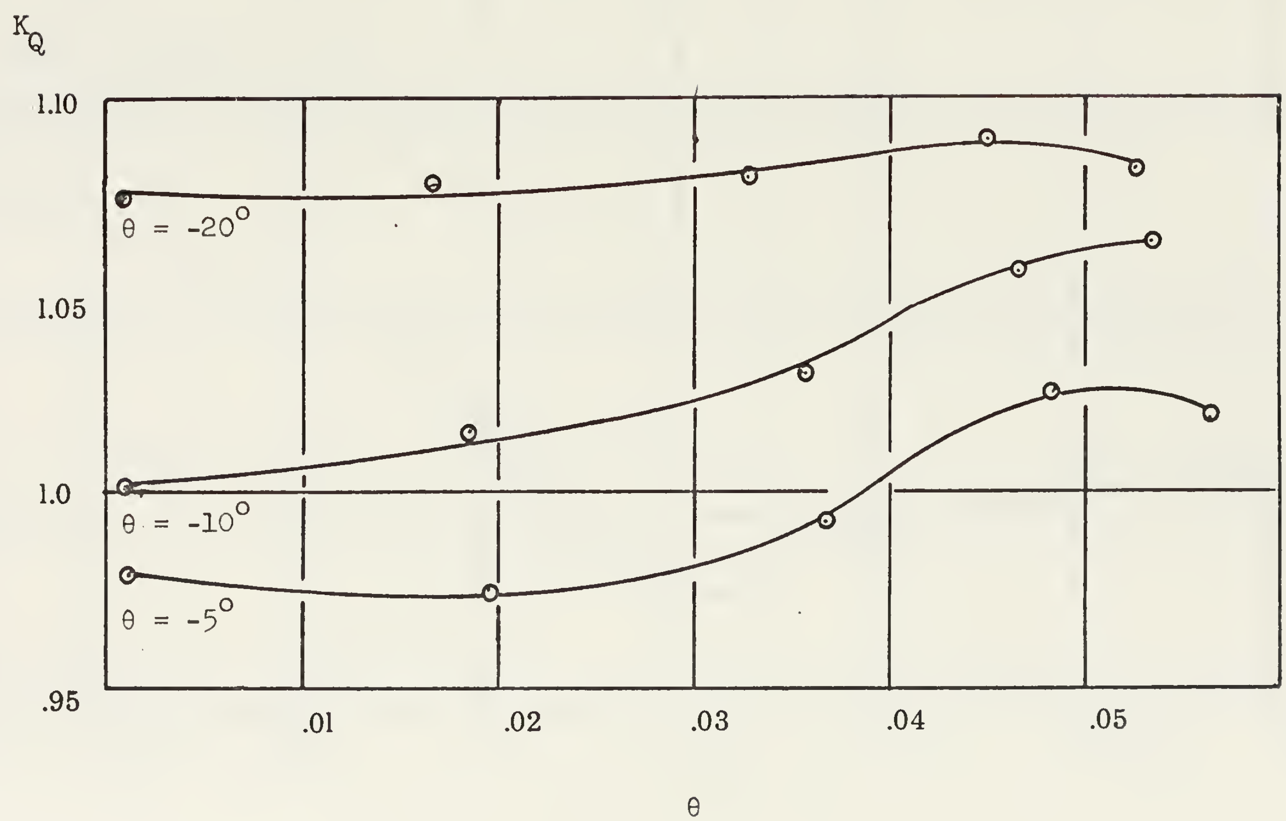


Figure 12: K_Q Versus M_r for 5-Hole Probe DA 120 #538 for $\theta = -5^\circ$, -10° and -20°

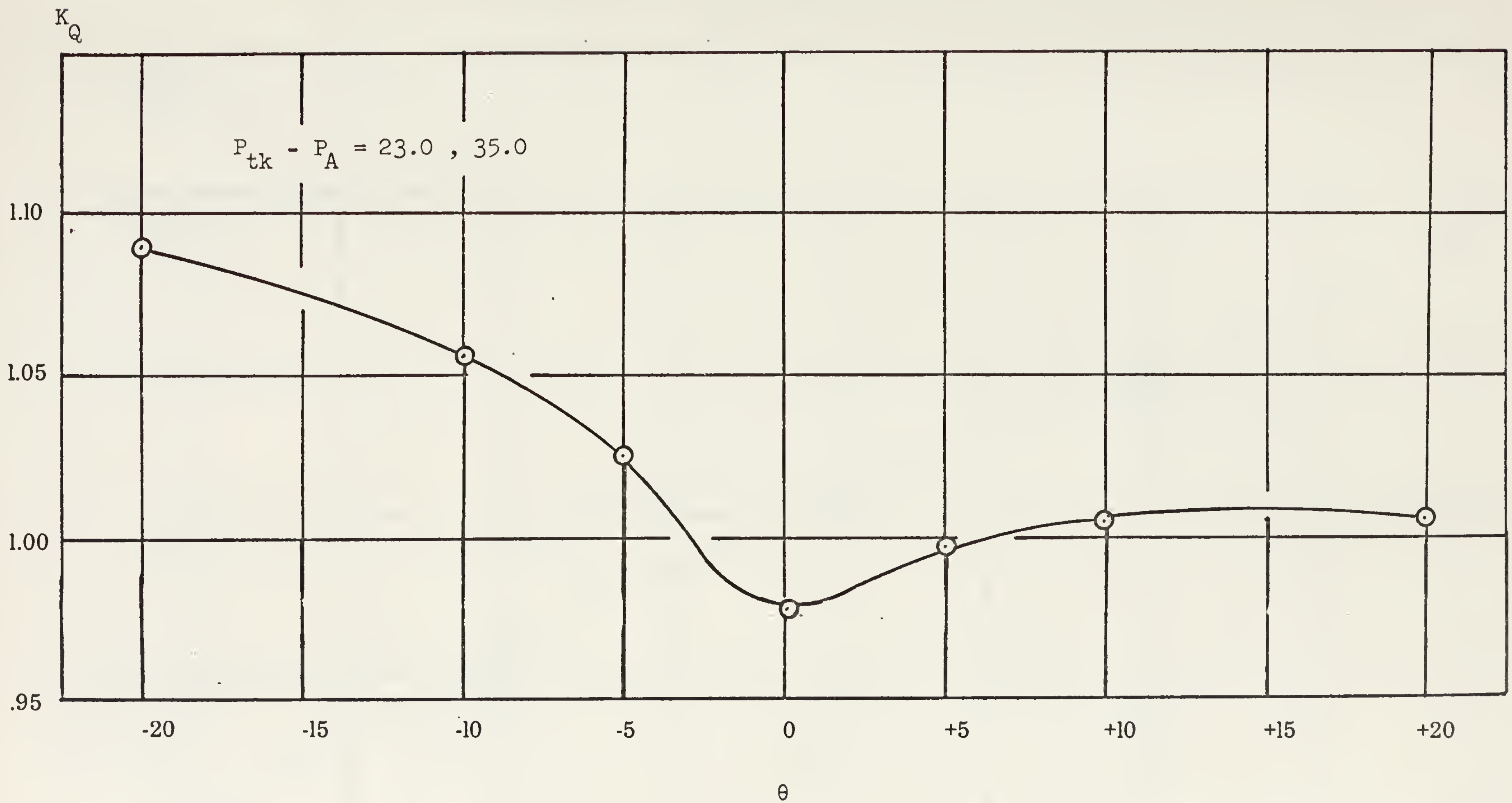


Figure 13: K_Q Versus Pitch Angle for 5-Hole Probe DA 120 #538

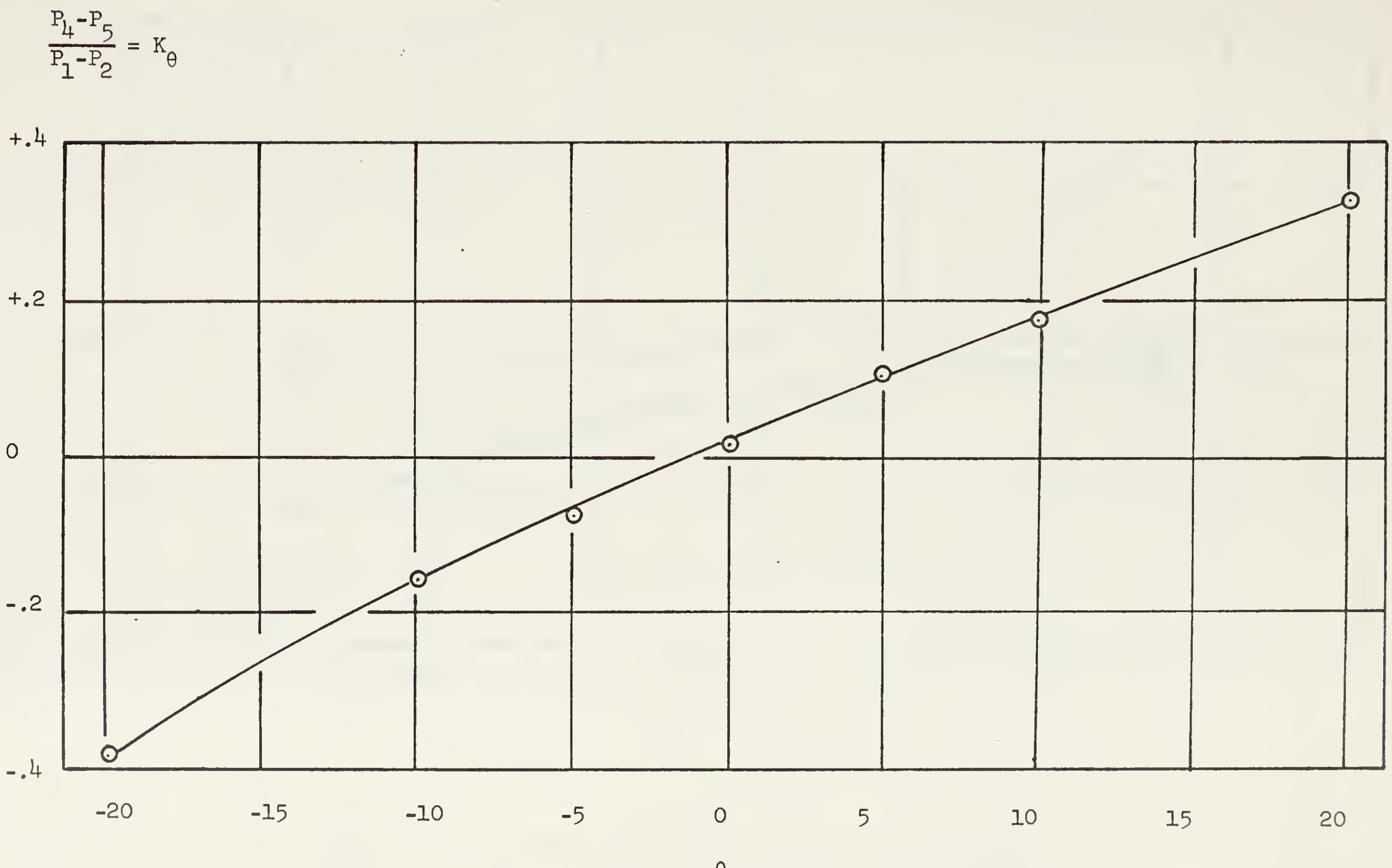


Figure 14. K_θ Versus θ For 5-Hole Probe DA 120 #538

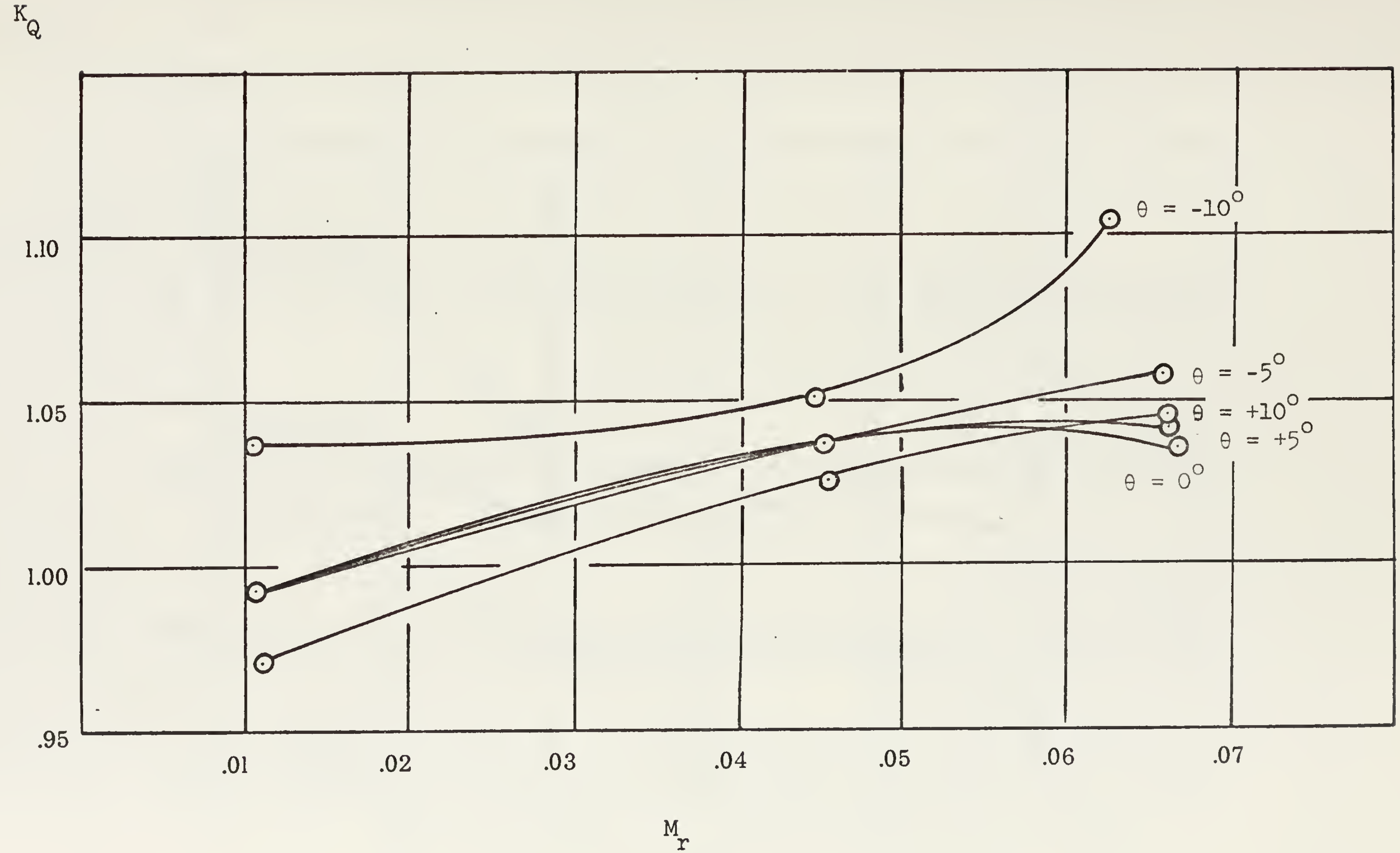


Figure 15: K_Q Versus M_r for 5-Hole Probe DA 120 #535

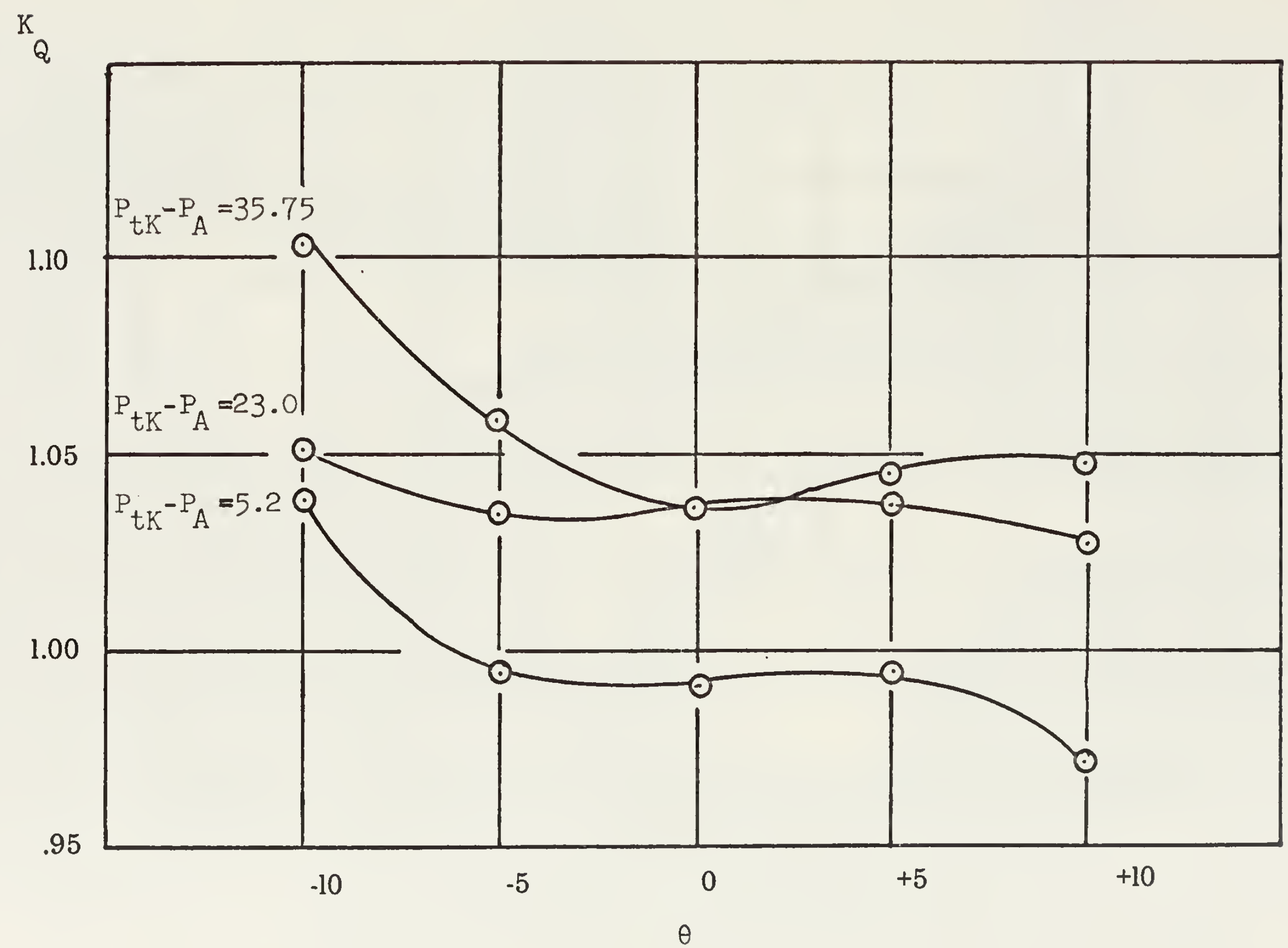


Figure 16: K_Q Versus Pitch Angle for 5-Hole Probe DA 120 #535

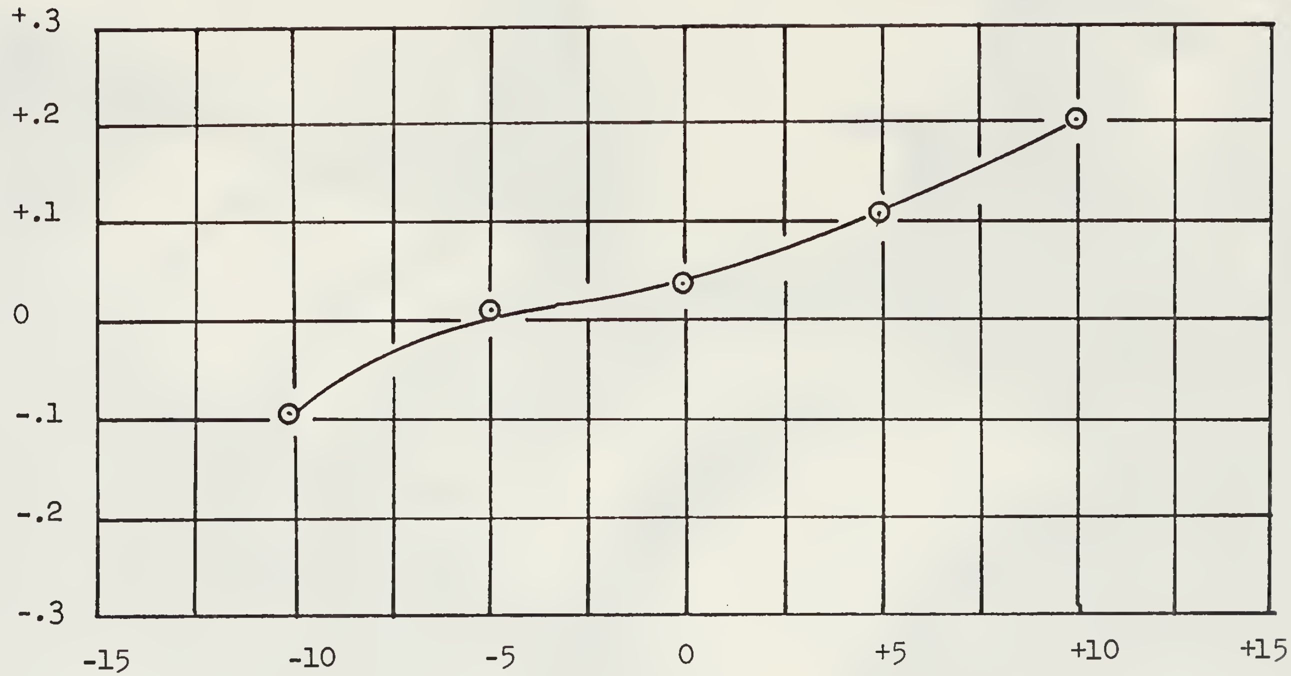


Figure 17. K_θ Versus Pitch Angle for 5-Hole Probe DA 120 #535

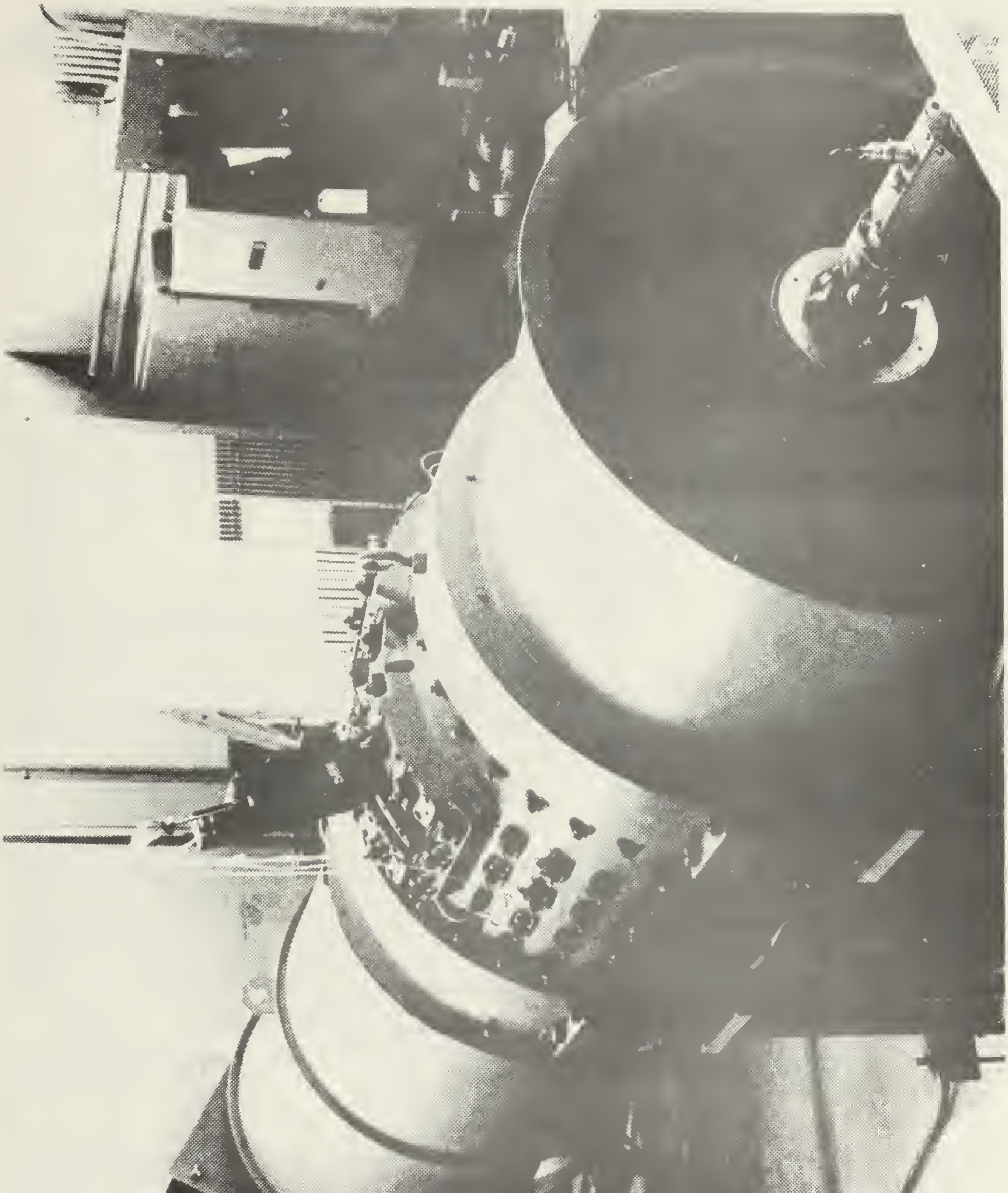


Figure 18. ONR Compressor Test Rig

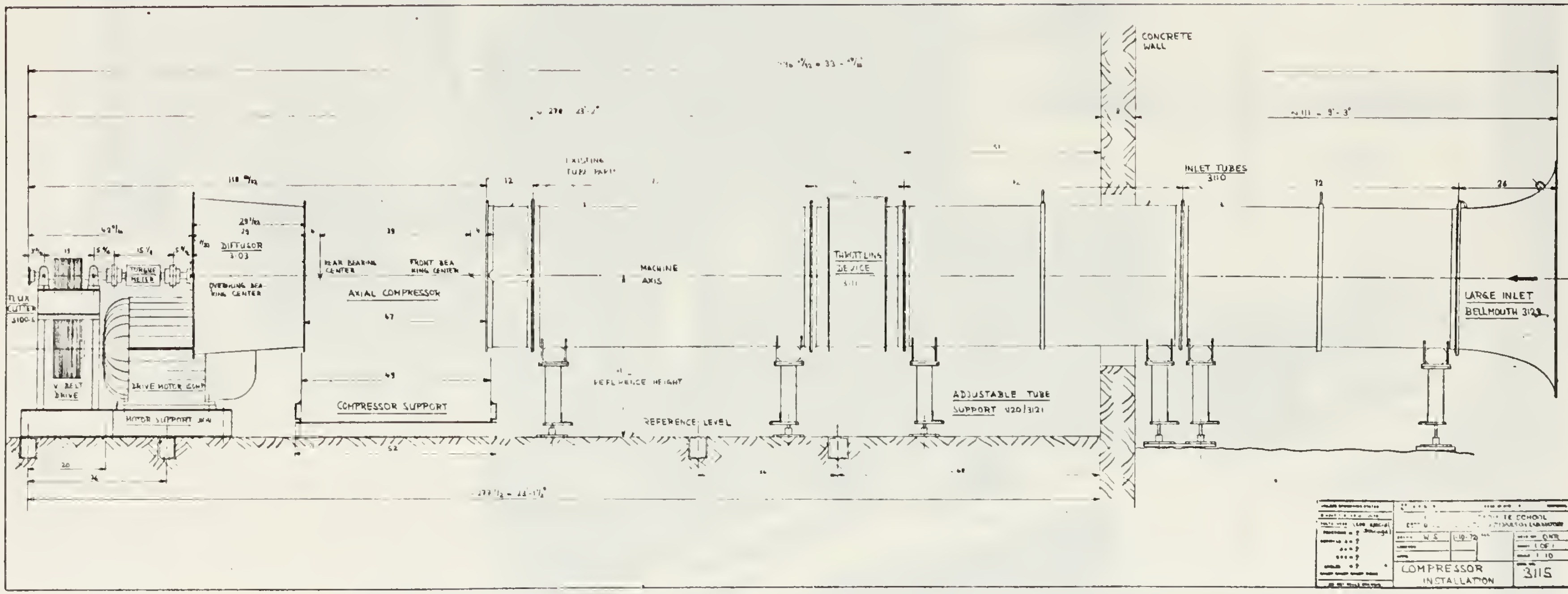


Figure 19. ONR Compressor Schematic

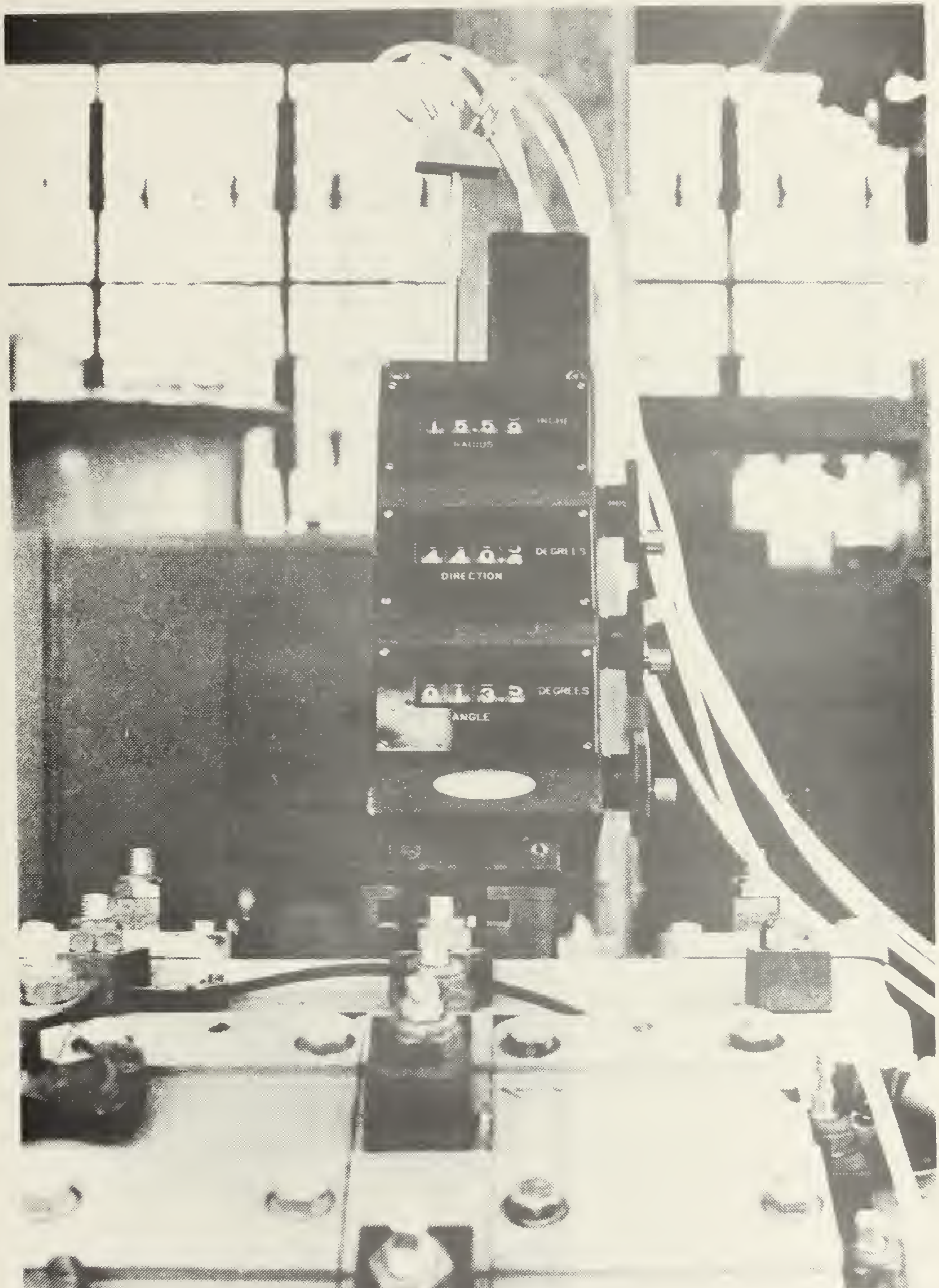


Figure 20. Survey Carriage

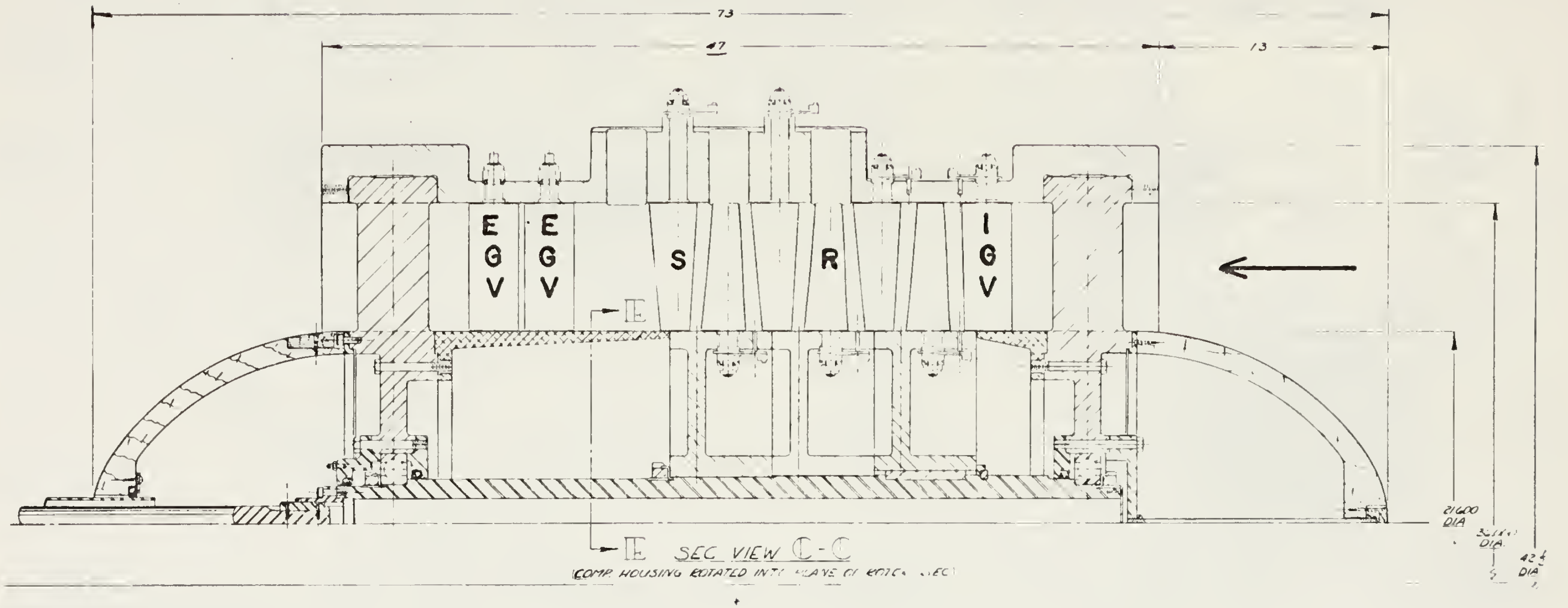


Figure 21. Compressor Sectional View Showing Installed Rotor and Stator

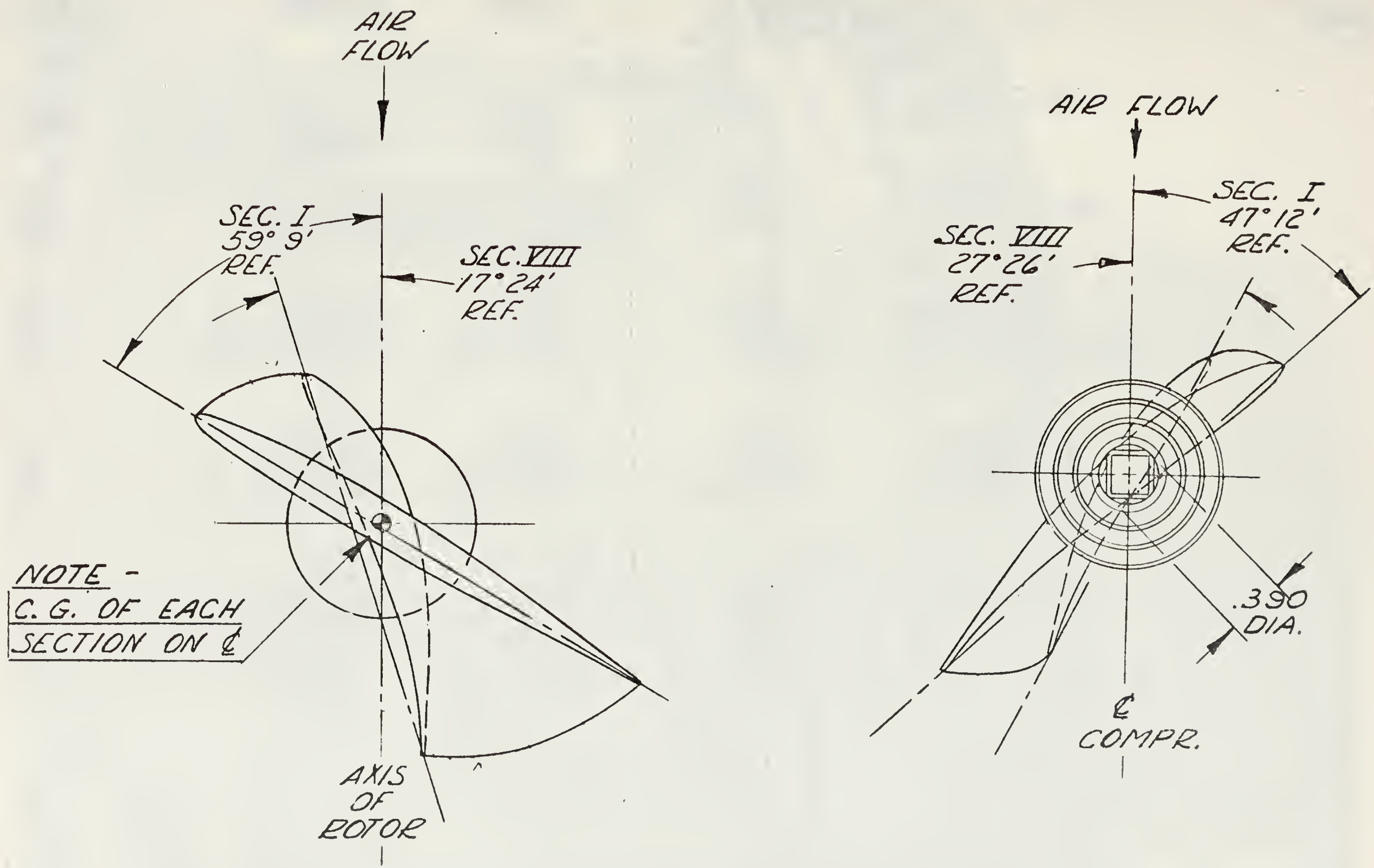


Figure 22. Solid Body Rotor and Stator Blades

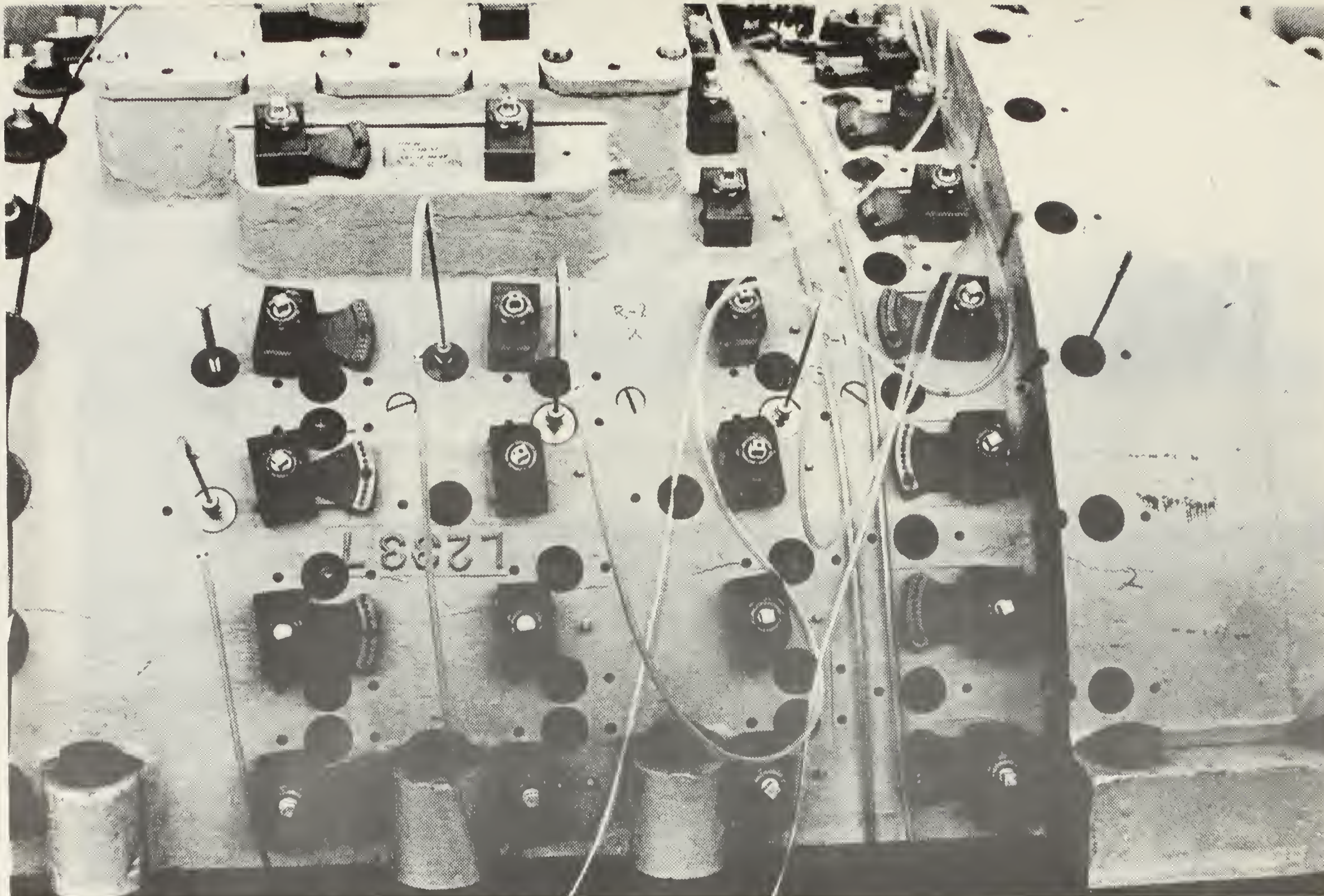


Figure 23. Kiel Probe Locations

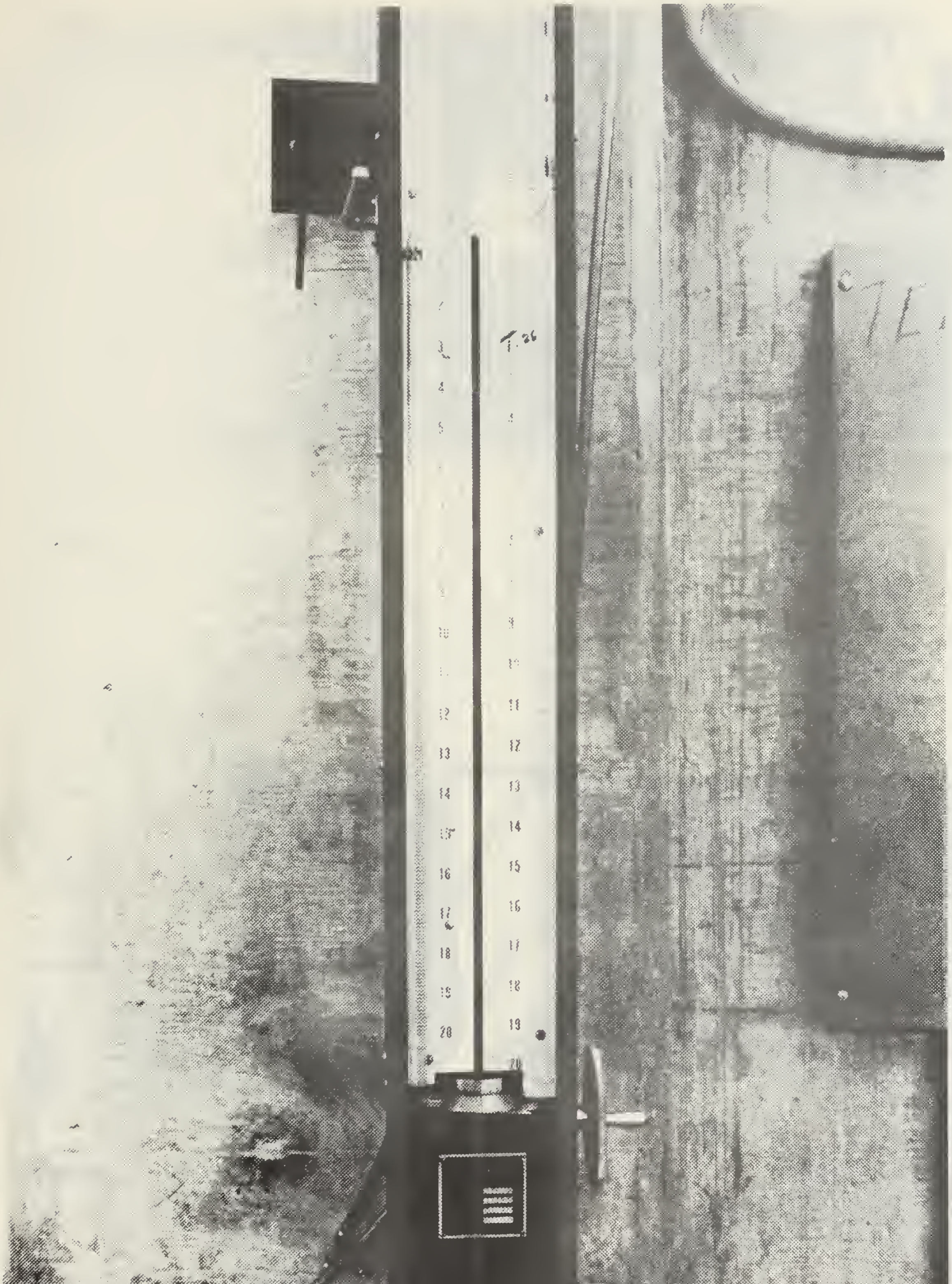


Figure 24. Meriam Micromanometer

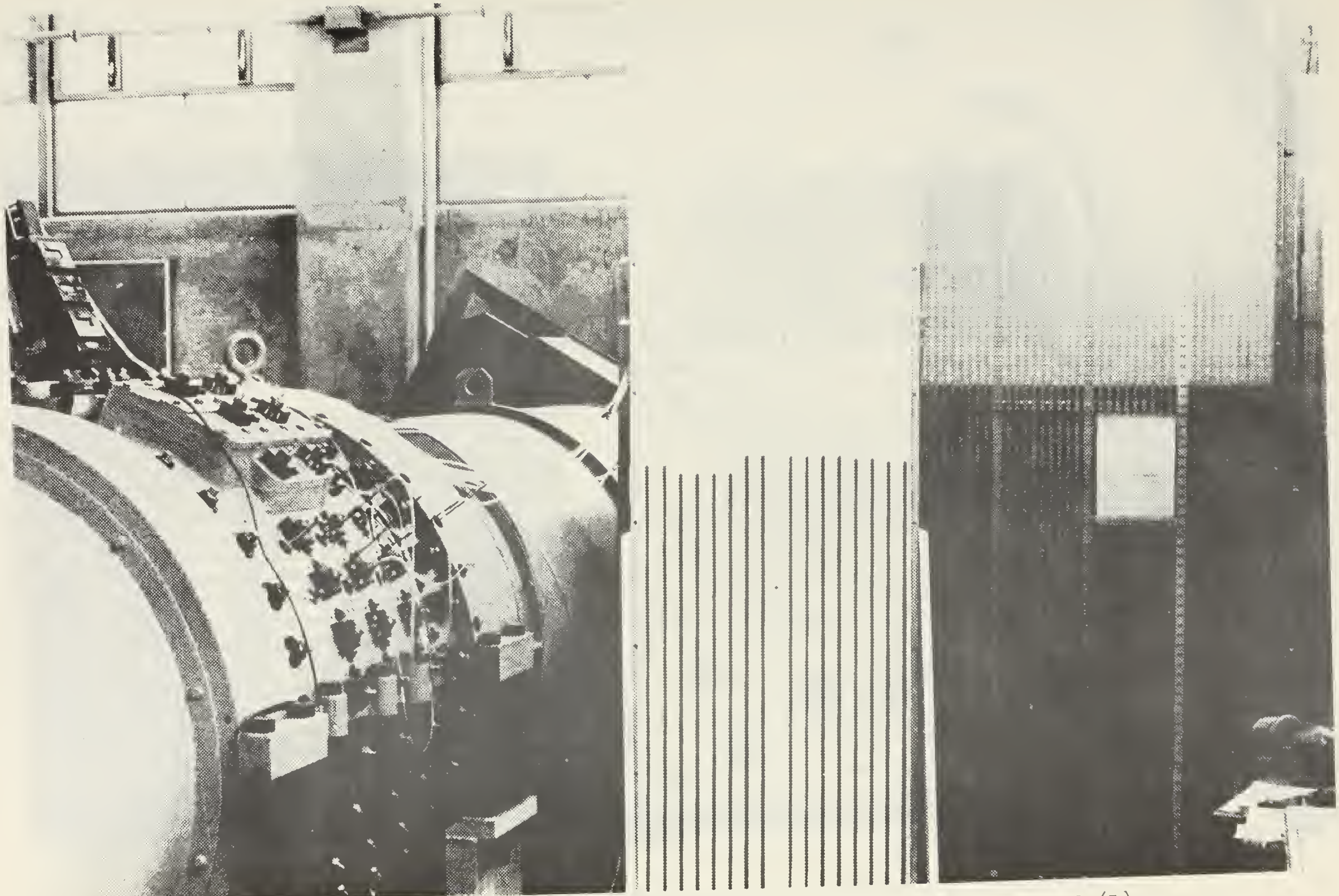


Figure 25. Large Water Manometer Board (R) and U-Tube Manometer Board (L)

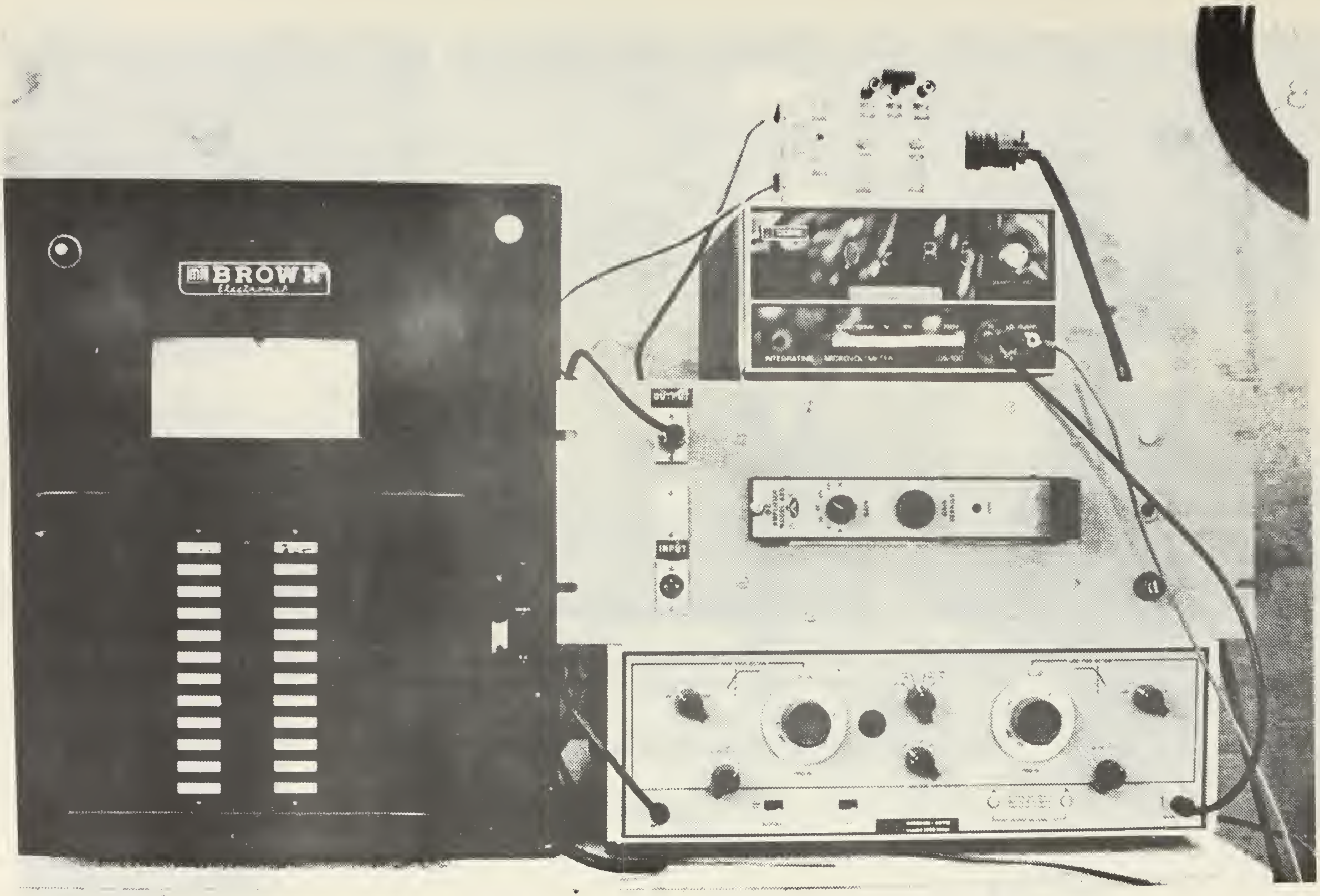


Figure 26. Bearing Temperature and Torque Measuring Equipment

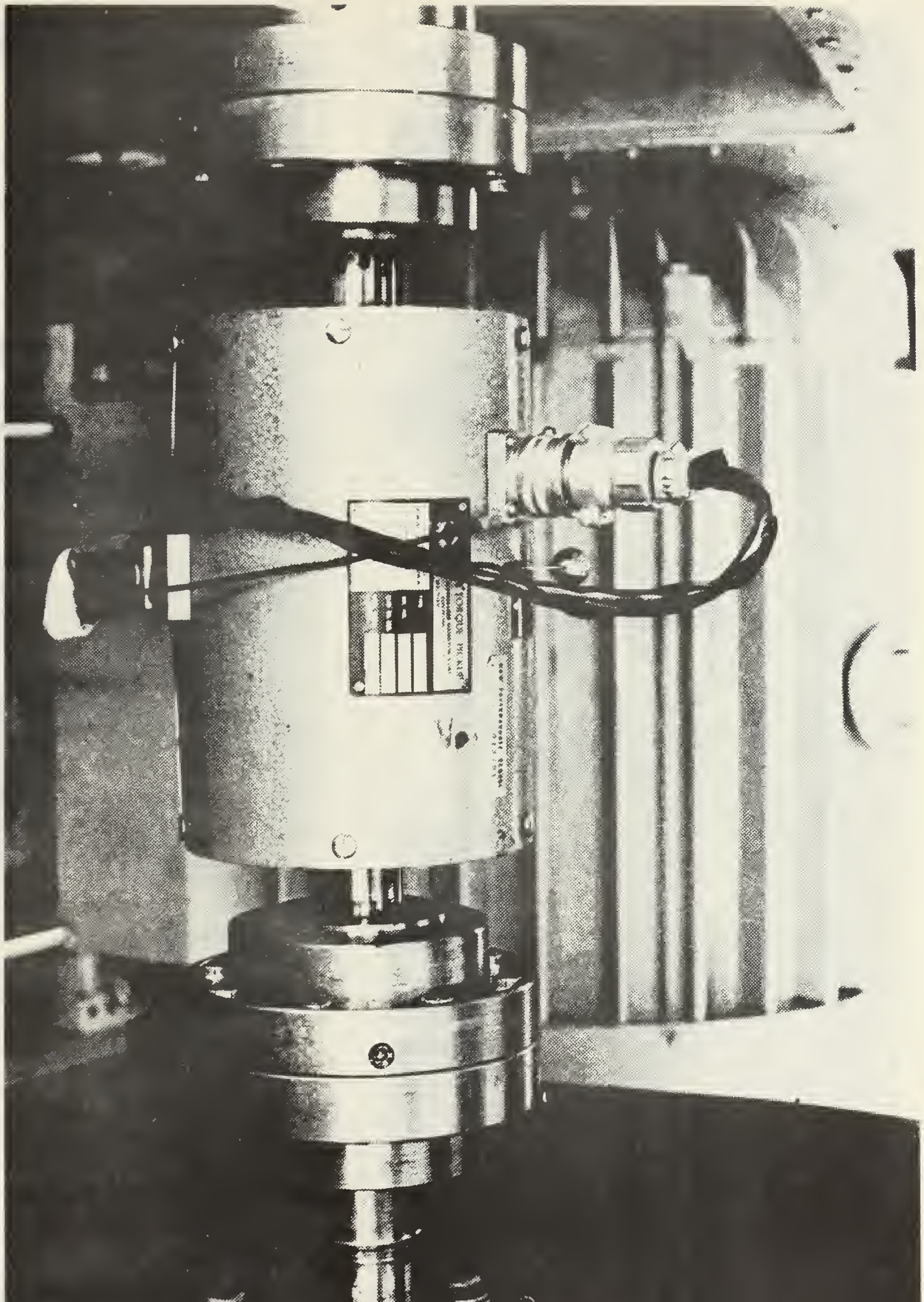


Figure 27. Torque Pickup

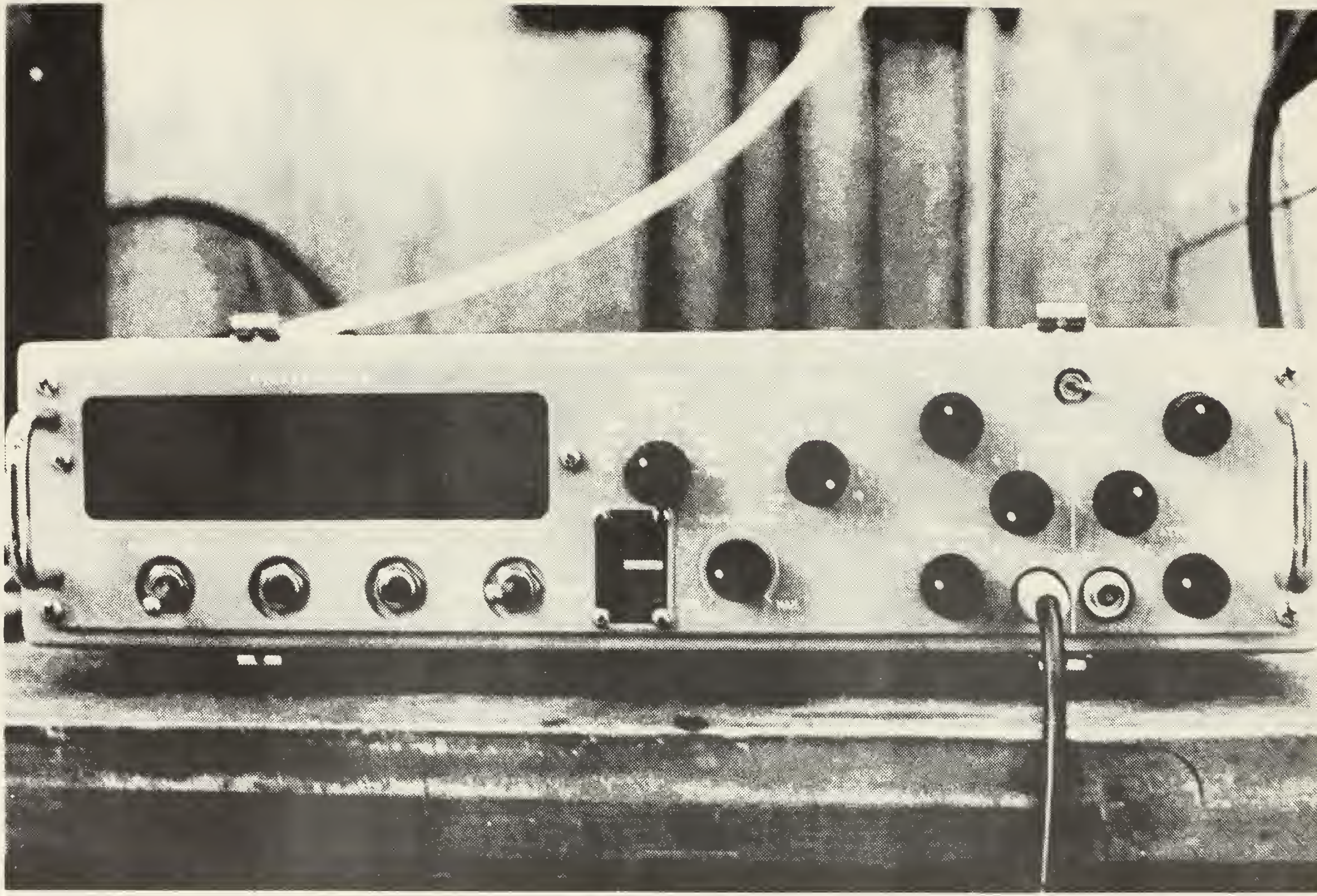


Figure 28. Rotational Speed Display Instrument

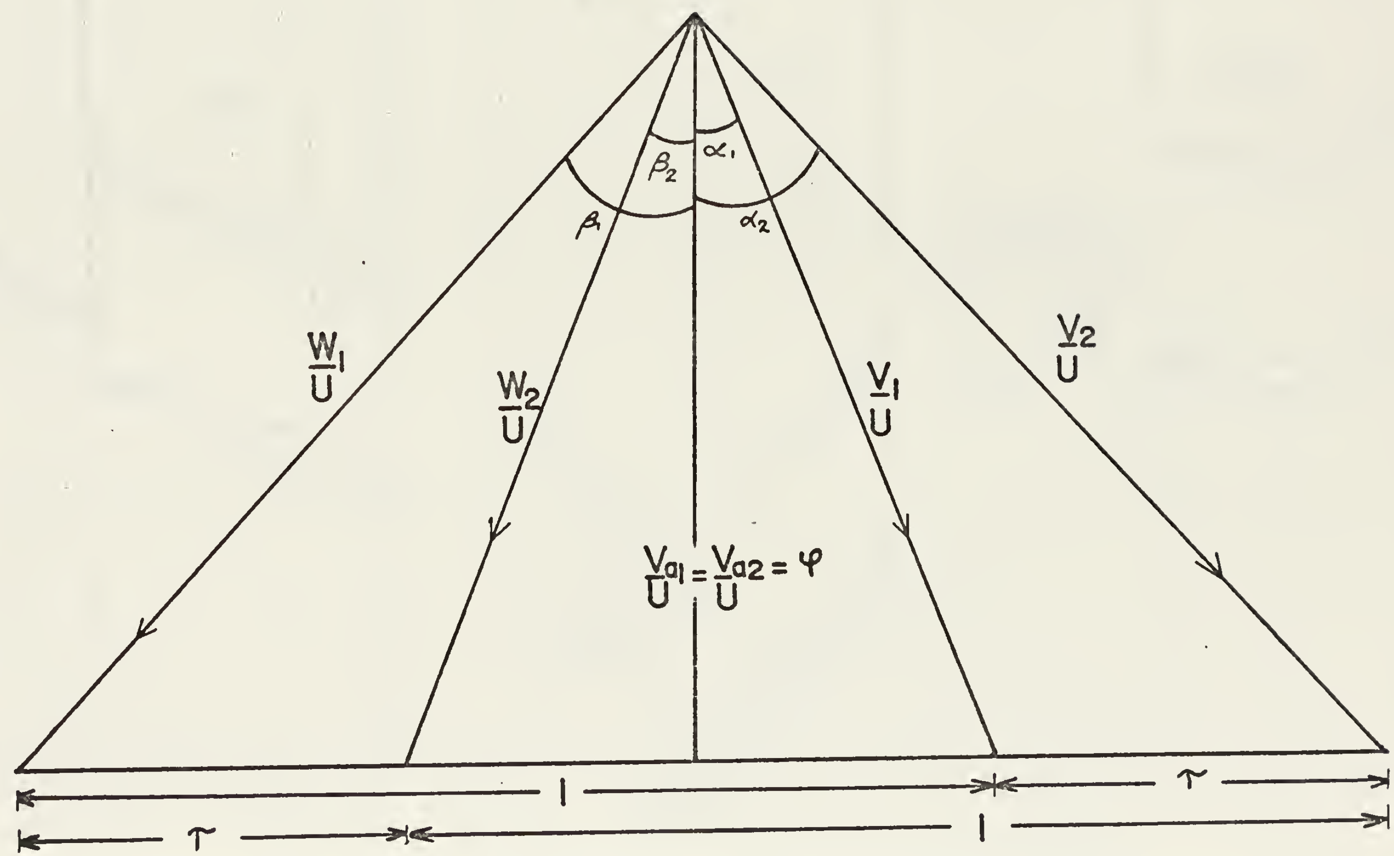


Figure 29. Non-Dimensional Velocity Diagram for 50% Reaction Blading

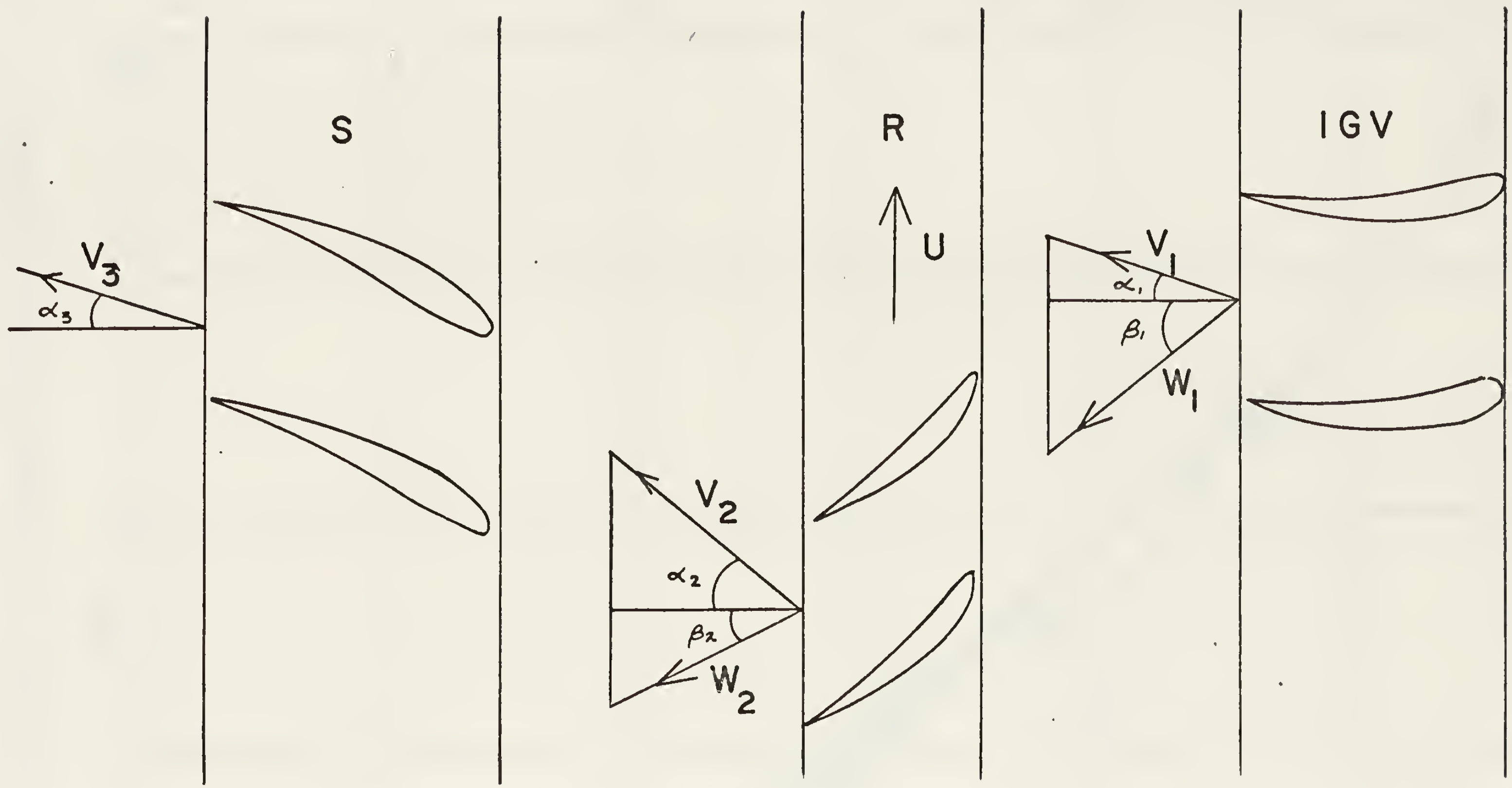


Figure 30. Compressor Stage for 50% Reaction Blading

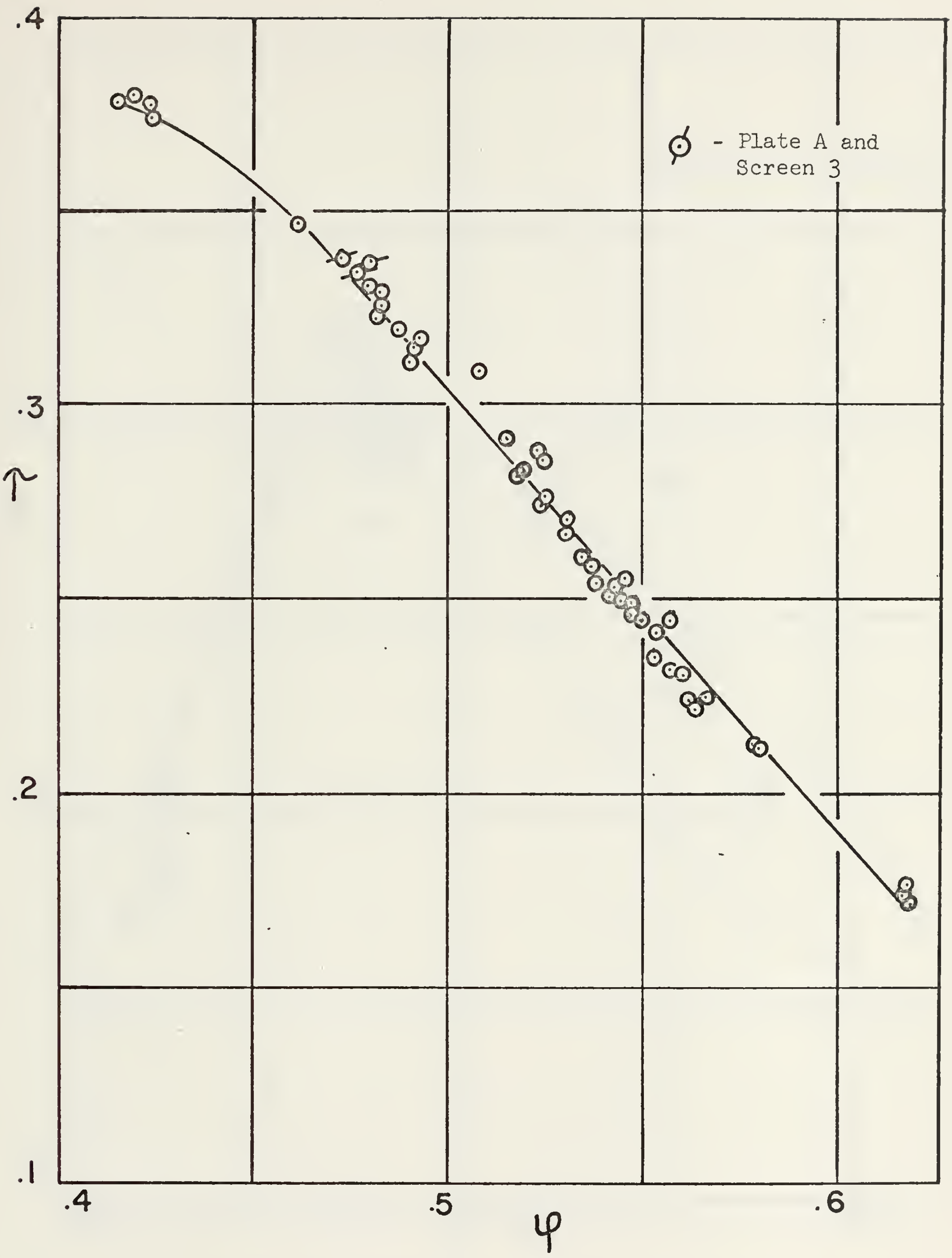


Figure 31. Work Coefficient τ Versus Flow Coefficient φ

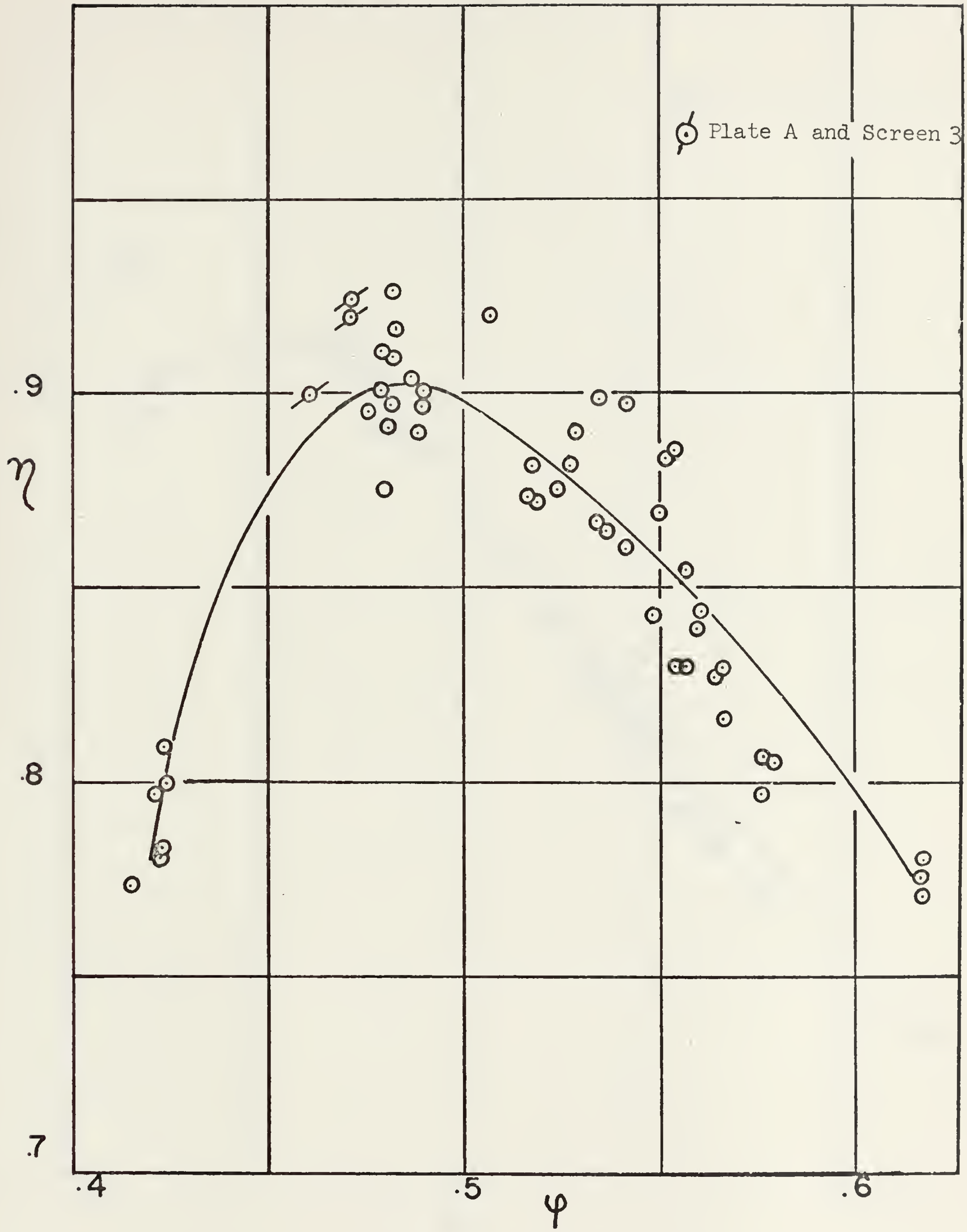


Figure 32. Efficiency η Versus Flow Coefficient φ

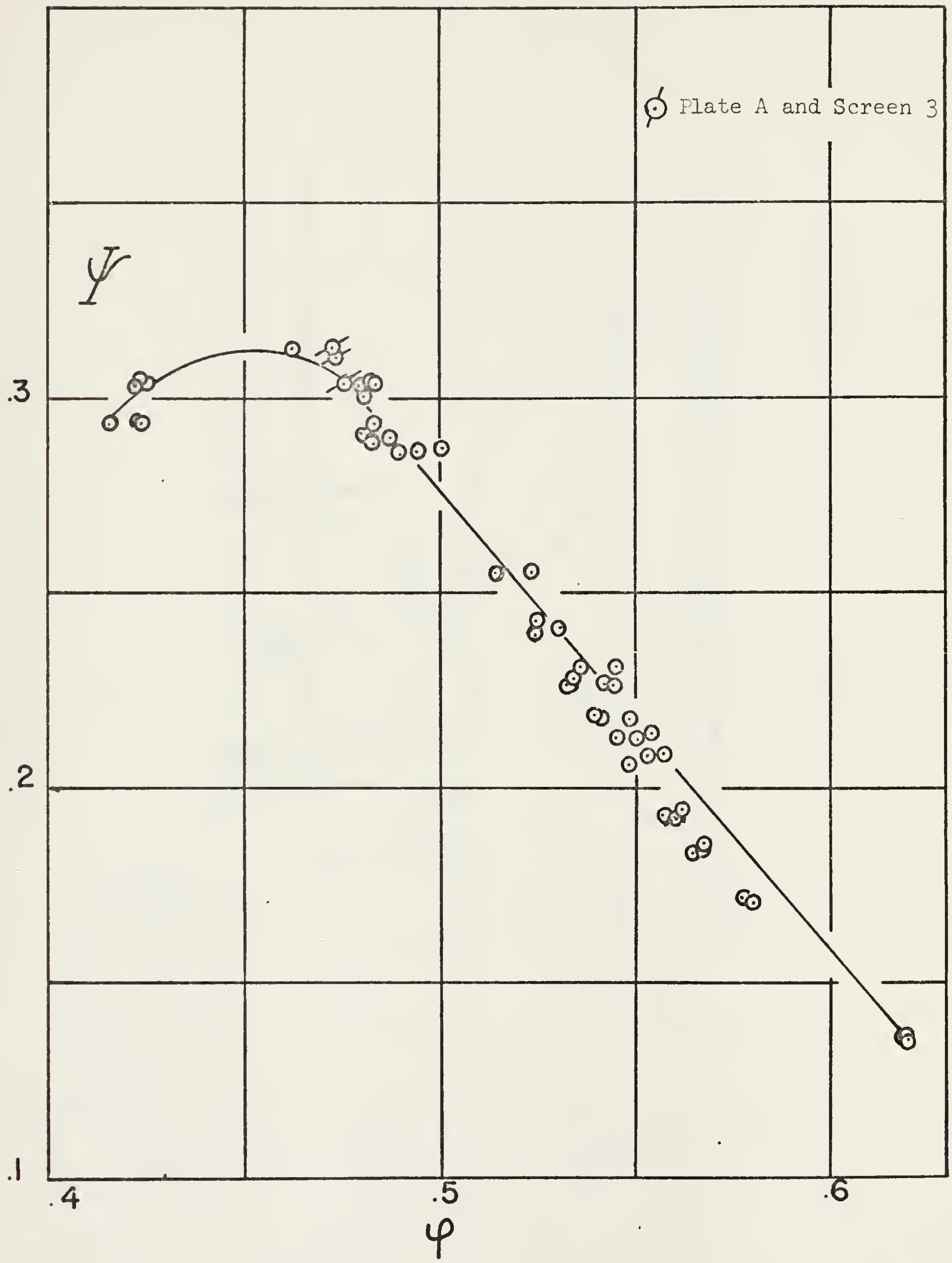


Figure 33. Head Coefficient Ψ Versus Flow Coefficient φ

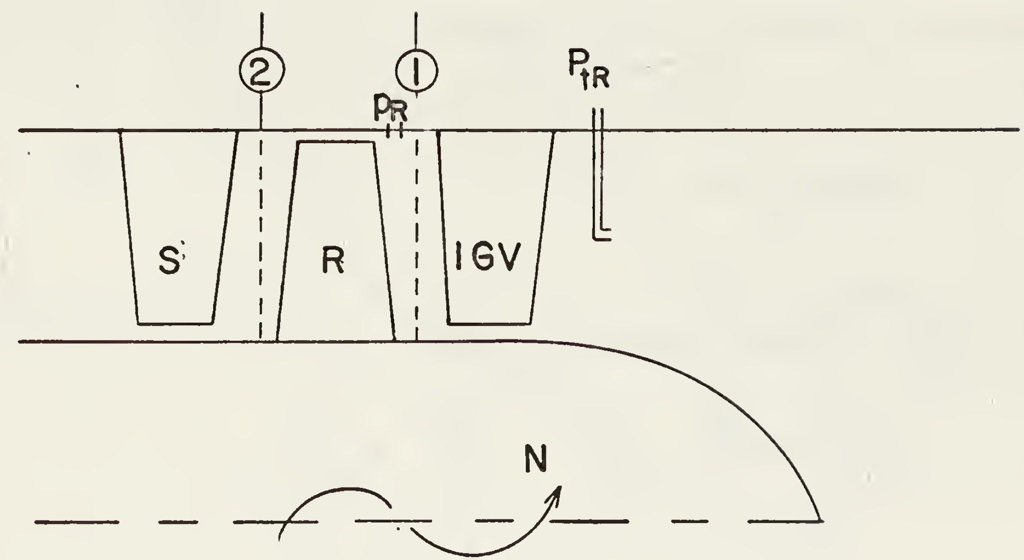


Figure 34. Schematic of Single Stage Arrangement

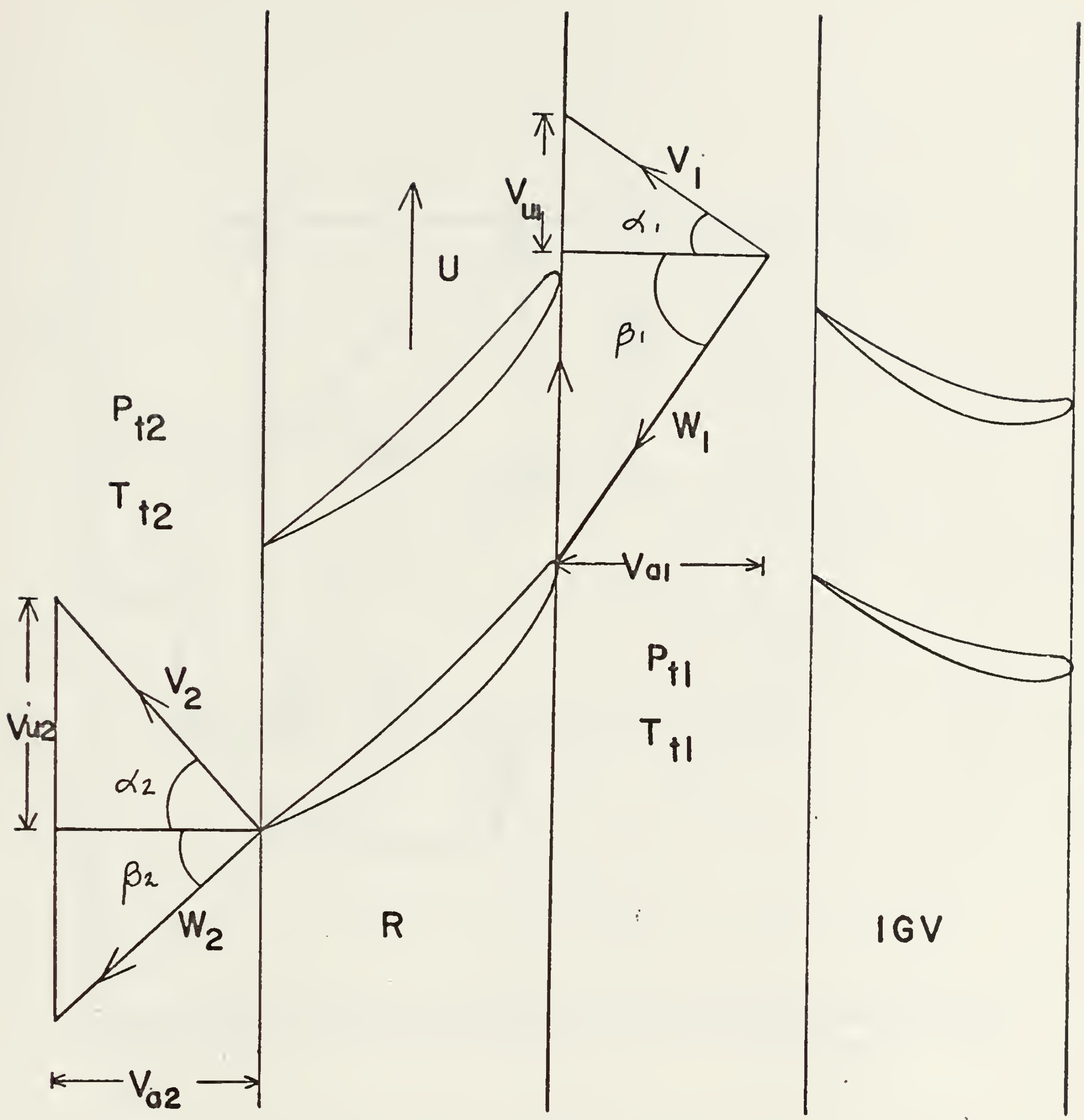


Figure 35. Blading at a Particular Stream Surface

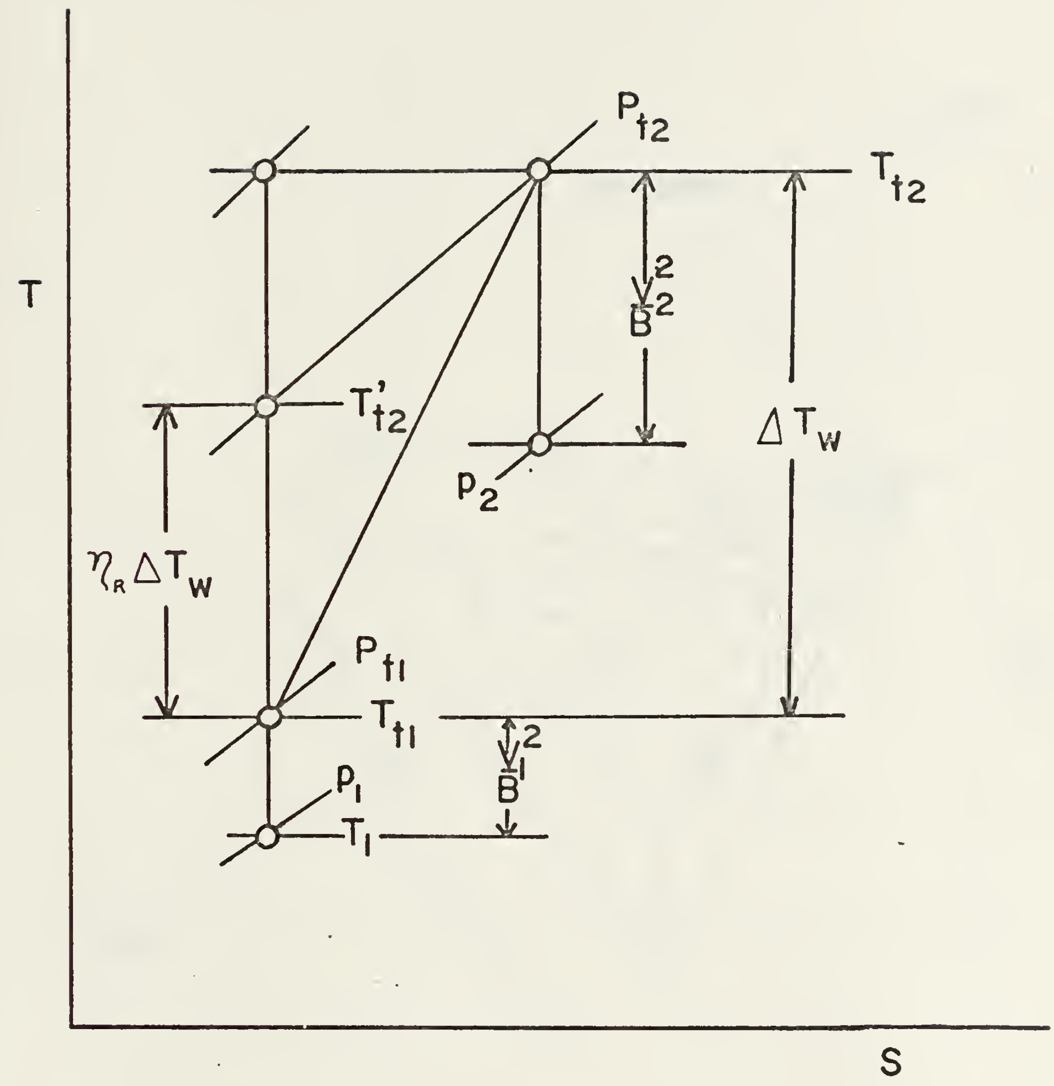


Figure 36. Temperature - Entropy Diagram of the Thermodynamic Process Across Rotor Blade ($B = 2gJC_P$)

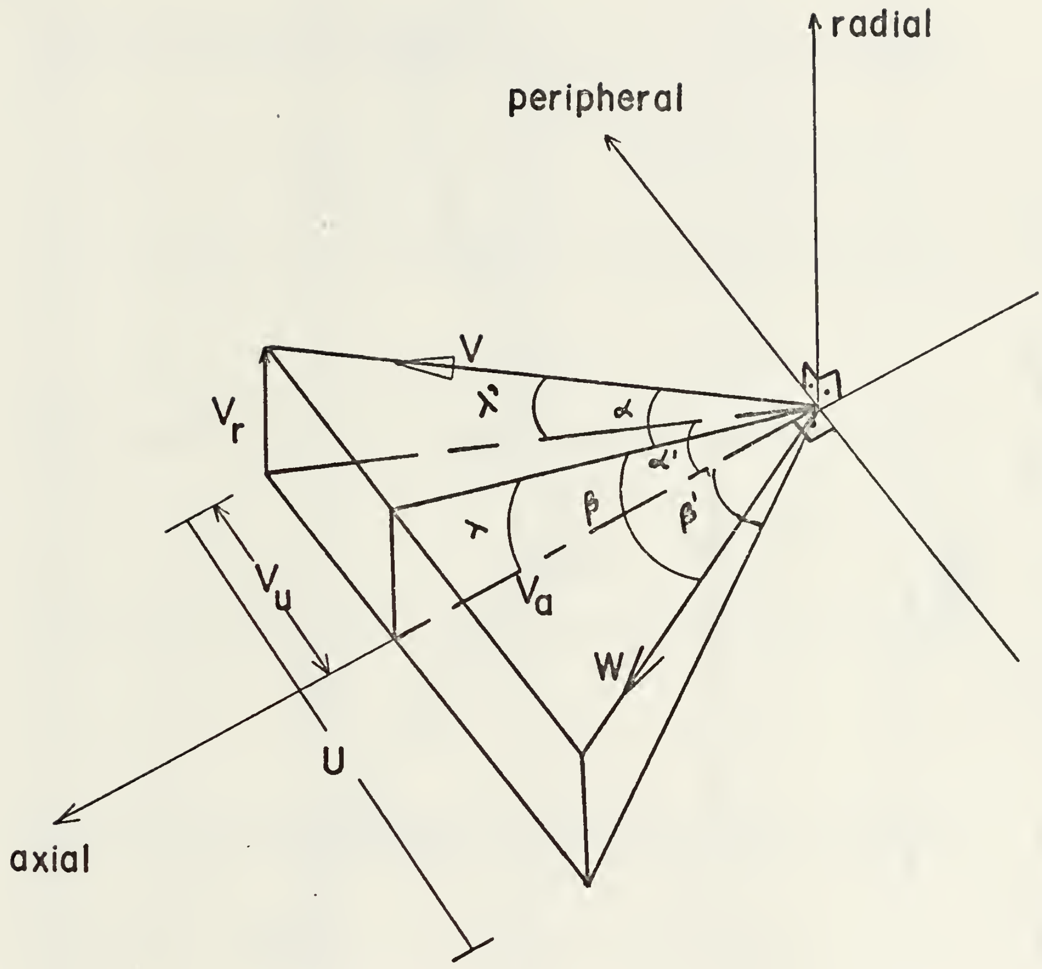


Figure 37. Velocity Diagram Showing Relationship Between Measured and Actual Flow Angles

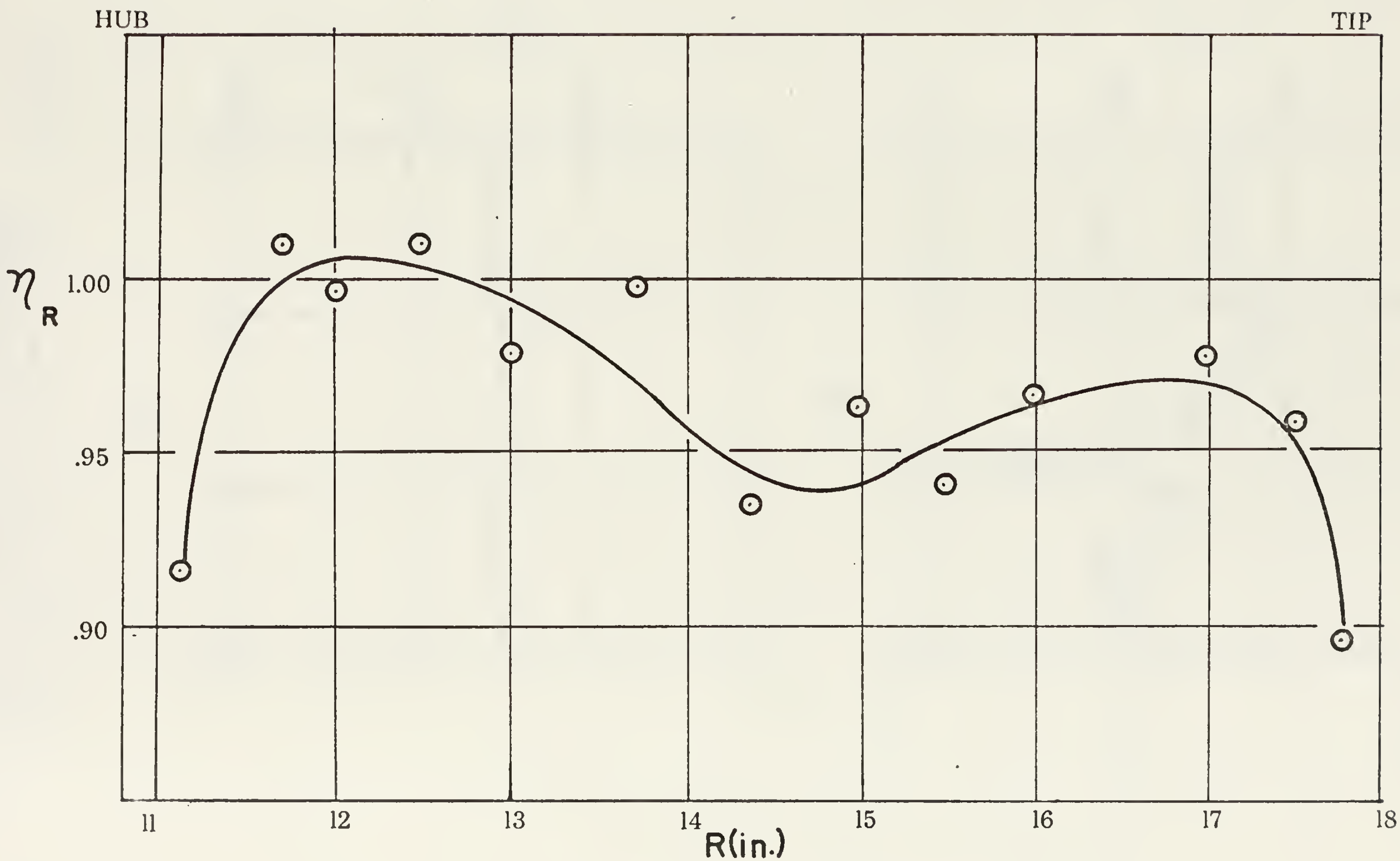
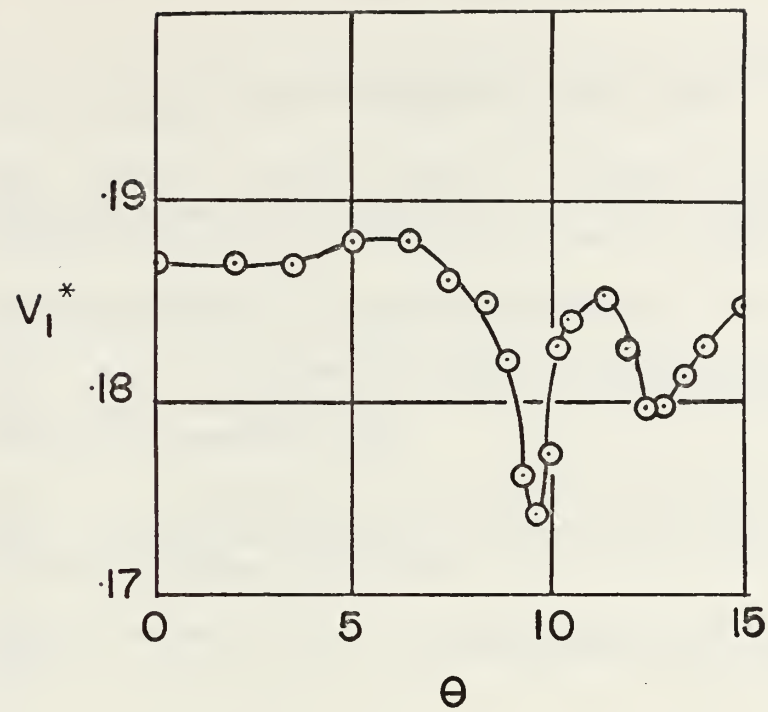


Figure 38. Efficiency η_R Versus Radial Position R



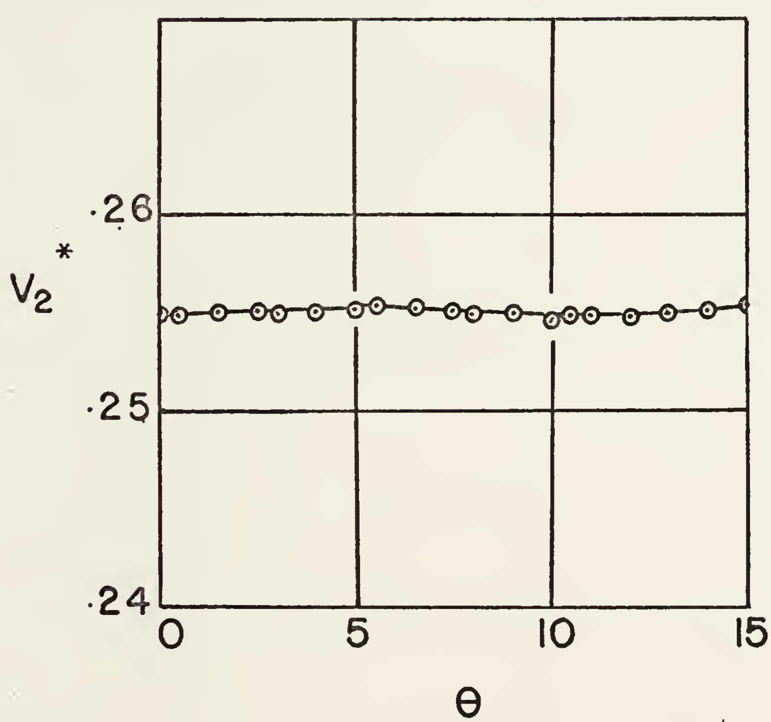


Figure 39. Velocity Before and After Rotor Versus Circumferential Position at R = 15.0 in.

LIST OF REFERENCES

1. Vavra, M. H., Aero-Thermodynamics and Flow in Turbomachines, John Wiley and Sons, Inc., New York, New York, 1960.

2. Bowen, John T., Sabersky, Rolf H., and Rannie, Duncan W., "Theoretical and Experimental Investigation of Axial Flow Compressors (Part 2)," California Institute of Technology, January 1949.

3. Standard Handbook for Mechanical Engineers, 7th ed., McGraw Hill, 1967.

4. Vavra, M. H., "Aerodynamic Design of Symmetrical Blading for Three-Stage Axial Flow Compressor Test Rig," Naval Postgraduate School, 57VA70091A, September 1970.

5. Gallo, S. F., "Comparison of Measured and Calculated Flow Properties After the Rotating Cascades of a Three-Stage Axial Compressor," Naval Postgraduate School, June 1968.

6. National Research Council, International Critical Tables, McGraw Hill, 1928.

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13. ABSTRACT

The objective of this study was to determine by experimental means the rotor efficiencies at different radii between hub and tip of a single stage axial compressor at its design point, to show the influence of tip clearance and end losses.

Procedures for calibration and application of pressure probes to survey the flow in the compressor were established, and programs were written to analyze the measured data.

Recommendations are made for improvements of the data reduction method, which should precede experiments involving controlled changes in the blade tip clearances.

KEY WORDS	LINK A		LINK B		LINK C	
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